AFRICA soil health consortium

Handbook for Integrated Soil Fertility Management

Edited by Thomas Fairhurst

Africa Soil Health Consortium: ***Handbook for Integrated Soil Fertility Management***

André Bationo (AGRA), Thomas Fairhurst (TCCL), Ken Giller (WUR), Valerie Kelly (MSU), Rodney Lunduka (CABI), Abdoulaye Mando (IFDC), Paul Mapfumo (SOFECSA), George Oduor (CABI), Dannie Romney (CABI), Bernard Vanlauwe (IITA), Lydia Wairegi (CABI), Shamie Zingore (IPNI).

Edited by Thomas Fairhurst

Please cite this publication as: Fairhurst, T. (ed.) (2012) *Handbook for Integrated Soil Fertility Management*. Africa Soil Health Consortium, Nairobi.

About the publisher

The Africa Soil Health Consortium (ASHC) mission is to improve the livelihoods of smallholder farmers through adoption of integrated soil fertility management (ISFM) approaches that optimize fertilizer use efficiency and effectiveness.

ASHC books are available at special discounts for bulk purchases. Special editions, foreign language translations and excerpts can also be arranged.

ISBN (e-book): 978 1 78064 285 7

ISBN (paperback): 978 1 78064 291 8

Typeset by Thomas Fairhurst, with SPi, Pondicherry, India.

Table of Contents

Foreword

The continent of Africa continues to grapple with many episodes of hunger and low crop productivity in multiple locations. With the ever-growing population in the continent, farmers continue to grow crops on the same land year after year. Under such continuous use, soil fertility declines if nutrients removed in crop products are not returned to the soil. To deal with this problem mineral fertilizers are essential. But as fertilizers are more expensive in Africa than anywhere else, most farmers use none at all. In response, many countries have subsidized fertilizers, yet often ignore supportive agricultural practices, institutions and policies. Increasing the productivity of smallholder farmers requires a good understanding of yield gaps (i.e. differences between actual, obtainable and potential yield under prevailing economic conditions) as well as biophysical and socio-economic factors constraints that hinder the closing of exploitable gaps.

Integrated soil fertility management, commonly referred to as ISFM, is presented in this handbook as a key contributor to Africa's low soil and crop productivity and especially for the main staples in the continent that include maize, beans, rice, cassava, bananas, sorghum, millet and other crops. In this context ISFM is defined as a set of soil fertility management practices that include the integrated use of mineral fertilizers, organic inputs and improved germplasms combined with the knowledge on how to adapt these practices to local conditions which are aimed at optimizing efficient agronomic use of the applied nutrients and thereby improving crop productivity. In this definition, all inputs need to be managed following sound agronomic and economic principles. ISFM cannot work if not supported by governments that are responsible for fertilizer imports, an enabled extension service that is critical to delivering the technology to the farmers, as well as a vibrant agro-dealer private sector that ensures efficient fertilizer and seed availability and distribution.

Over the past 10 years, many publicly funded research initiatives have been conducted on ISFM across sub-Saharan Africa (SSA). Work on ISFM has mainly been written in technical reports and scientific papers published in peer-reviewed journals. The idea for a practical ISFM handbook emerged from a needs assessment and consultations undertaken in preparation for a grant application to the Bill & Melinda Gates Foundation by CABI. The concept of an Africa Soil Health Consortium (ASHC) was proposed earlier by a group of ISFM experts in a consultation meeting held at Wageningen, The Netherlands, in 2010. These experts form the nucleus of the Consortium's technical advisory group (TAG), which provides both advice and technical capacity to support the creation of ISFM information materials such as this handbook. The handbook synthesizes the learning that has accumulated on ISFM in a publication that can be used to train practitioners.

The funding to produce this handbook and other learning materials under the ASHC has been provided by the Bill & Melinda Gates Foundation, which commits the Consortium, coordinated by CABI, to work in collaboration with experts to develop core reference materials on ISFM principles (referred to as Level 1 products) in English, French and Portuguese versions. This is what has culminated in the production of this handbook. The first consultative meeting on the book was held in May 2011 during the launch of the project in Nairobi, Kenya.

The majority of work to develop this handbook was undertaken at a write-shop held in Nairobi in October 2011 with the key authors working with Thomas Fairhurst, ASHC's technical editor. In November 2011, Paul Van Mele of Agro-Insight, a private communication company, visited six countries in West, Central and East Africa to make a film (with narration in English, French and Portuguese) that reflects the principles of ISFM outlined in the handbook illustrated by the footage from the project's priority cropping systems. The film can be viewed online at http://www.cabi.org/ashc.

This book is meant for training of extension workers in soil fertility management techniques in SSA and for workers involved in rural development that would like to learn more about the principles and practices of ISFM. This handbook is also a useful primer on ISFM for education organizations such as universities and technical colleges, organizations involved in the development of policy on agriculture and rural development that need reference materials on ISFM techniques, and other government and non-government organizations (NGOs) seeking to implement ISFM.

The ISFM handbook is organized into seven sections that include: an introduction, the need for ISFM, the principles of ISFM, soil fertility management practices, targeting ISFM options, an introduction to soil and crop production and a section containing tables, definitions and reference information. The entire project team that includes the TAG hopes that the reader finds this handbook a useful tool for tackling soil fertility and management on the continent and elsewhere where similar factors of production are at play.

Signed:

Peter Okoth (CIAT)
Shamie Zingore (IPNI)
André Bationo (AGRA)
Thomas Fairhurst (TCCL)
Ken Giller (WUR)
Rebbie Harawa (AGRA)
Jeroen Huising (CIAT)
Bashir Jama (AGRA)
Richard Jones (IFDC)
Valerie Kelly (MSU)
Abdoulaye Mando (IFDC)
Paul Mapfumo (SOFECSA)
Paul Van Mele (Agro-Insight)
Kabirou Ndiaye (AfricaRice)
George Oduor (CABI)
Bell Okello (ICRW)
Bernard Vanlauwe (IITA)

Acknowledgements

The preparation of this handbook was supported by the Bill & Melinda Gates Foundation.

The authors wish to thank Simon Ndonye for the wonderful illustrations, Leonard Rusinamhodzi for preparing the glossary and Priscilla Sharland for proof reading the handbook. Thanks also go to the following organizations for the time the authors spent writing the different sections of the handbook (in alphabetical order):

1. Alliance for a Green Revolution in Africa (AGRA)
2. CAB International (CABI)
3. International Center for Soil Improvement and Agricultural Development (IFDC)
4. International Institute of Tropical Agriculture (IITA)
5. International Plant Nutrition Institute (IPNI)
6. Michigan State University (MSU)
7. Soil Fertility Consortium for Southern Africa (SOFECSA)
8. Tropical Crop Consultants Ltd (TCCL)
9. Wageningen University (WUR)

Photographs used in this handbook were provided by André Bationo, Ken Giller, Bernard Vanlauwe, Thomas Fairhurst, Paul Mapfumo, Shamie Zingore, Abdoulaye Mando, Pablo Tittonell, Paul Van Mele, Lieven Claessens, Jeff Bentley, Dannie Romney, Lydia Wairegi and George Oduor.

Some of the figures used are based on published resources.

Tables 7.2–7.4, 7.6–7.33, 7.36, 7.38, 7.39, 7.41 and 7.42 have been reproduced from *Soil Fertility Kit*, with kind permission from IPNI.

About CTA

The Technical Centre for Agricultural and Rural Cooperation (CTA) is a joint international institution of the African, Caribbean and Pacific (ACP) Group of States and the European Union (EU). Its mission is to advance food and nutritional security, increase prosperity and encourage sound natural resource management in ACP countries. It provides access to information and knowledge, facilitates policy dialogue and strengthens the capacity of agricultural and rural development institutions and communities.

CTA operates under the framework of the Cotonou Agreement and is funded by the EU.

For more information on CTA, visit www.cta.int

1 Introduction

1.1 Introduction

In this section we will define integrated soil fertility management (ISFM), explain why we felt the need for the handbook and describe how the handbook can be used for farming systems development in sub-Saharan agriculture (SSA).

1.2 What is integrated soil fertility management (ISFM)?

In this publication we define ISFM as:

> A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at optimizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic and economic principles.

1.3 How the handbook came about

Over the past 10 years, much publicly funded research has been carried out on ISFM across SSA. Work on ISFM has mainly been written up in reports and scientific papers published in peer-reviewed journals. The idea for a practical ISFM handbook emerged from the needs assessment and consultations undertaken in preparation for a grant application to the Bill & Melinda Gates Foundation by CABI. Experts that took part in this consultation became the nucleus of the Africa Soil Health Consortium (ASHC) technical advisory group (TAG), which provides both advice and technical capability to support the creation of ISFM extension materials such as this handbook. The handbook synthesizes the learning that has accumulated on ISFM in a publication that can be used to train practitioners.

The grant provided by the Bill & Melinda Gates Foundation commits ASHC to work in collaboration with experts to develop core reference materials on ISFM principles (referred to as Level 1 products) in print-ready form in English, French and Portuguese versions. The Foundation application also commits ASHC to produce high-quality film material for broadcasting, ensuring that the messages are effectively communicated with translations into the same three languages.

The majority of work to develop this handbook was undertaken at a write-shop held in Nairobi in October 2011. The ASHC brought together experts on ISFM from the TAG together with CABI staff from the project implementation group.

The group of experts first developed an outline that was finalized at the meeting. The write-shop was a collaborative process where participants wrote and then critiqued each other's work to move to a consensus about the style and content of the finished text. Thomas Fairhurst, ASHC's technical editor, led this process and edited the handbook.

In November 2011, Paul Van Mele (Agro-Insight), visited six countries in West, Central and East Africa to make a film (with narration in English, French and Portuguese) that describes the principles of ISFM. He captured different practices in the project's priority cropping systems:

- maize/legumes;
- lowland irrigated rice;
- sorghum/millet/cowpea;
- banana/coffee; and
- cassava-based systems.

He also developed a film to explain to policy makers why and how support for ISFM development and dissemination is important for improving the livelihoods of smallholder farmers in SSA.

1.4 Who are these materials designed for?

It is anticipated that these materials will be useful for training extension workers in soil fertility management techniques in SSA and for workers involved in rural development that would like to find out more about the principles and practices of ISFM.

This handbook is also a useful primer on ISFM for education organizations such as universities and technical colleges, organizations involved in the development of policy on agriculture and rural development that need reference materials on ISFM techniques, and other government and non-government organizations (NGOs) seeking to implement ISFM.

This handbook is defined by ASHC as **Level 1** or core reference material on ISFM principles (Figure 1.1). This handbook has been prepared based on a review of published papers, grey literature and existing extension materials. The ASHC plans to produce **Level 2** core reference materials on the major cropping systems in SSA that incorporate ISFM principles and practices. Locally adapted **Level 3** extension materials will also be produced in collaboration with extension agencies and NGOs active at local level in selected countries.

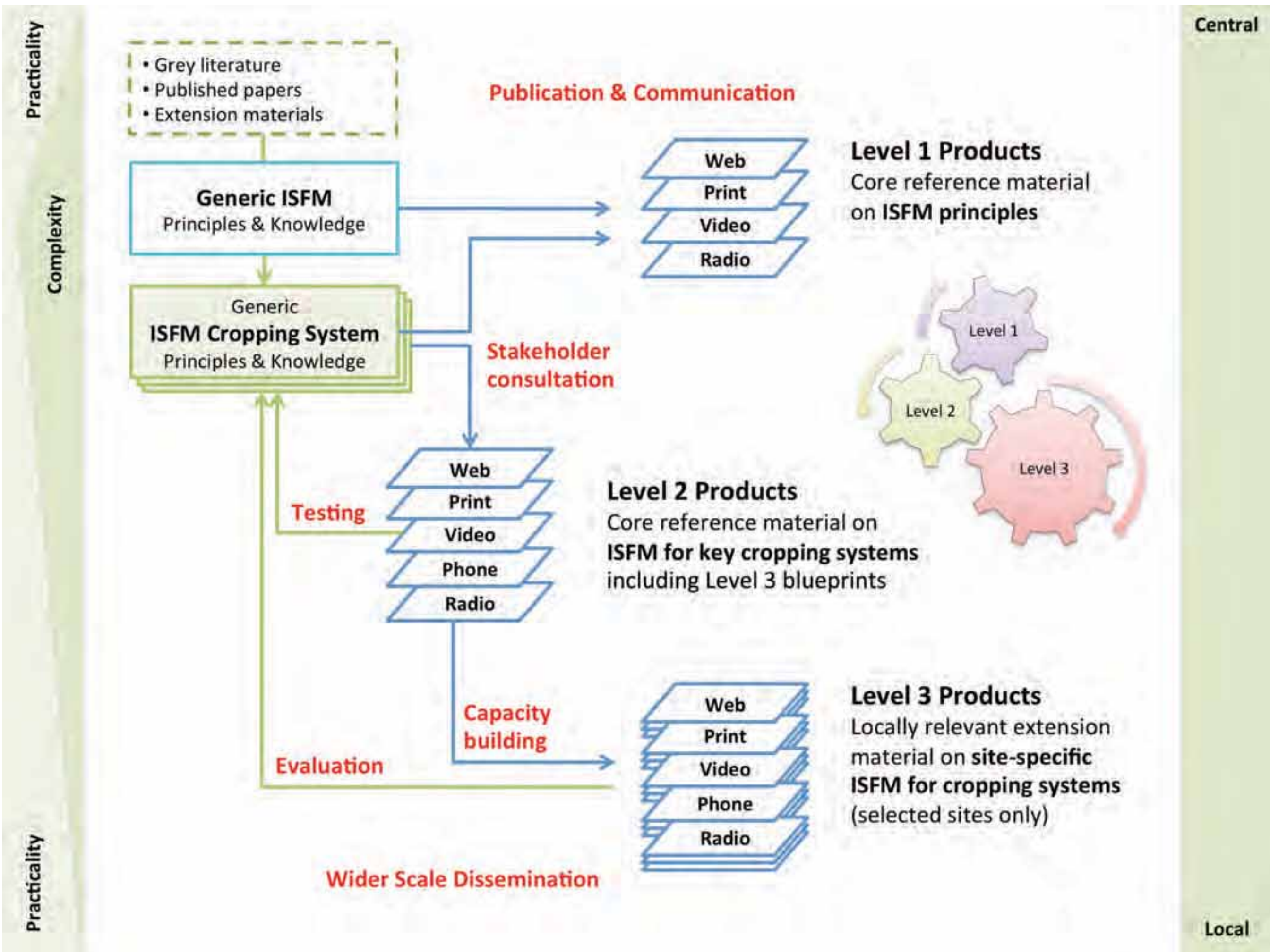


Figure 1.1 Process for the preparation of extension materials on ISFM in common cropping systems.

1.5 Contributors

Production of this handbook would not have been possible without the support of the Bill & Melinda Gates Foundation.

ASHC would like to thank the following people who gave generously of their time to make this resource possible. They also ensured that the content allows adaptation of technical knowledge to local contexts for different user groups.

TAG members

- André Bationo, Alliance for a Green Revolution in Africa (AGRA)
- Thomas Fairhurst, Tropical Crop Consultants Ltd (TCCL)
- Ken Giller, Wageningen University (WUR)
- Valerie Kelly, Michigan State University (MSU) with the support of United States Agency for International Development (USAID)
- Abdoulaye Mando, International Center for Soil Improvement and Agricultural Development (IFDC)
- Paul Mapfumo, Soil Fertility Consortium for Southern Africa (SOFECSA)
- George Oduor, CABI
- Bernard Vanlauwe, International Institute of Tropical Agriculture (IITA)
- Paul Van Mele, Agro-Insight
- Shamie Zingore, International Plant Nutrition Institute (IPNI)

ASHC delivery team

- Rodney Lunduka, CABI
- George Oduor, CABI
- Dannie Romney, CABI
- Lydia Wairegi, CABI

For biographical and contact details see: www.cabi.org/ashc

ASHC is also grateful to everyone who has contributed ideas and feedback to make this collaborative process a success.

2 The need for ISFM

2.1 Introduction

In this section we first provide the context and relevance of this handbook, and explain why we need to move from 'silver bullet' to 'best-fit' solutions built on the principles of integrated soil fertility management (ISFM) for farming systems development in sub-Saharan Africa (SSA).

2.2 The context

Over the next 40 years the population of SSA is set to increase by 700 million inhabitants. This translates into a massive increase in the need for food, feed, fibre and fuel, in a region where many countries already import significant amounts of food. But how can food, feed, fibre and fuel production be increased? While it is likely that there will continue to be some further expansion in the area cultivated, there are many competing claims on land for urban development and for wilderness. Given current crop yields there is great potential to increase agricultural production through intensification of production on land already under cultivation.

Yield intensification is usually concerned with increasing the yield of crops but may also involve increasing the *number* of crops grown in each field each year. In addition to the sparing of land for other uses, yield intensification has benefits of increasing returns to labour (i.e. reducing the drudgery of intensive labour investment for little return), and increasing farmers' food self-sufficiency and incomes. The bulk of SSA's food requirements will continue to be produced by small-scale farmers who represent about 70% of the population in SSA.

The term 'smallholder farmer' is an umbrella term that encompasses a huge diversity of types of farms within a myriad of farming systems. We can make a distinction between two types of small-scale farmers:

- farmers engaged in the production of crop products and livestock for sale in local markets; and
- farmers engaged in agriculture either to achieve food security or as a sideline activity to supplement livelihoods based on employment or small-scale business activity.

In both farm types, improvements in soil fertility can contribute to increased yields but the appropriate approach to soil fertility improvement may be very different. For example, farmers linked into the market are usually in a stronger position to borrow money from the bank and invest in inputs (improved seed, fertilizers, agrochemicals) by comparison with farmers producing for local consumption who may not be able to borrow money to purchase inputs and are often averse to the risk of investing in agricultural inputs. For this reason, ISFM places great emphasis on adapting proven principles of soil fertility management to the farmer's situation and goals (i.e. production for the market or for local consumption).

Improvement in agricultural productivity by small-scale farmers – the so-called 'Green Revolution' – has underpinned the economic developments that have taken place over the past 50 years in Asia. Industrial development has taken place but food security has been maintained at regional and often national levels, and small-scale farmers now benefit from expanded markets for their products in rapidly growing cities. The Green Revolution focused attention on improving productivity in lowland, and usually irrigated, rice-based systems where variability between farms is much less than the variability between farms and landscapes found in SSA. The emphasis was placed on wide-scale implementation of 'best-bet' technologies that could be implemented effectively across large areas.

As we shall see, farming system development in SSA requires very different technologies and approaches to productivity improvement to those used successfully in the predominantly irrigated farming systems in Asia. Nevertheless, some features are common to both regions, particularly with regard to the role of the state as:

- a **primary driver** of agricultural productivity improvement in small-scale farms;
- a **source of finance** for infrastructure and institutions required to better integrate farmers into markets for inputs (i.e. fertilizers, seeds, agrochemicals and credit) and outputs; and
- a **source of research and extension** leading to the dissemination of information on appropriate technologies for soil fertility management to a diverse range of farmers.

ISFM has the greatest potential for impact in SSA in areas where:

- there is a need for crop intensification due to high and increasing population; and
- farmers have access to markets for their products.

2.3 Farming systems development in sub-Saharan Africa (SSA)

Kofi Annan, the former Secretary General of the United Nations, called for 'a uniquely African Green Revolution in the 21st century', that should recognize the rich diversity of Africa's people, soils and farming practices as well as the urgent need to increase agricultural productivity. But how do we develop and target ISFM technologies to improve productivity given the huge diversity and heterogeneity of African farming systems?

African agriculture is highly diverse, with major farming systems matched to each of the main agroecologies. Zooming in within each of these broad classes of farming systems we find another level of substantial variability at more local levels. Within any given country or region there are also more localized gradients of rainfall, and large differences between regions in terms of socio-economics and access to markets. Even down to the village level, there is a wide diversity of farming livelihoods differing in production objectives, wealth and resource endowment.

Much of the heterogeneity within the farming systems is caused by spatial variability in soil fertility, which arises due to two main factors:

- First, inherent differences that arise due to the parent material from which the soil has evolved and the position in the landscape that influences how soil develops. Together these are often referred to as the 'soilscape'. A large proportion of soils in Africa are derived from some of the oldest land surfaces in the world with few nutrients left. Where younger, volcanic soils occur these are inherently richer in nutrients, but may have other soil fertility problems such as fixation of phosphorus into forms that cannot be easily accessed by crops.
- Second, past management by farmers has a major influence on soil fertility. In a shifting cultivation, or bush fallow system, soil fertility of a field will be influenced by how long it has been cultivated since the last fallow period and the length of the fallow period. On small, intensively managed farms the quantities and quality of organic manures and fertilizers that have been added to the soils in the past will determine the current soil fertility status. If manure is only applied to fields close to the homestead, strong soil fertility gradients can be seen and soil fertility usually declines as you walk further from the house.

Smallholder farms are not always market oriented. While some families 'make a living' out of agriculture, others keep the family land for other reasons (e.g. a 'place to stay', social insurance) and regard agriculture as a secondary activity. Many rural families in Africa are below the poverty line and cultivate crops on land that is already degraded. It is too simplistic to assume that promoting the use of agricultural inputs through price policies or subsidies will automatically and sustainably boost productivity and improve livelihoods. This is particularly the case when rural families have diverse sources of income and perhaps hope to leave agriculture at some time in the future.

All soil-improving technologies have a cost in terms of labour and land. Further, as both mineral fertilizers and organic matter are scarce nutrient resources, ISFM focuses on how to manage them efficiently. The approach described in this handbook represents a substantial shift in concepts away from the idea of 'blanket recommendations' for fertilizers. Instead the focus is on how to target ISFM technologies to different farmers and crops within their farms. We suggest simple 'rules-of-thumb' that have been derived from scientific principles and local farmers' knowledge and tested thoroughly in the field.

2.4 Targeting technologies – from 'silver bullets' to 'best fits'

It is clear that 'one-size-fits-all' or 'silver bullet' solutions that can be applied across large regions do not exist for SSA. Instead, technologies need to be targeted to farming systems and farms while recognizing their agroecological and socio-economic environments – to different 'socio-ecological niches'. So instead of talking about baskets of 'best-bet' technologies we prefer to refer to locally adapted ISFM technologies as 'best-fit' options.

- **One-size-fits-all** or **silver bullet** solutions attempt widespread implementation of a particular approach without adaptation to the local situation.
- **Best-bet** solutions are adapted to some situations.
- **Best-fit** solutions are specifically adapted to the local situation.

New approaches to the problem of poor soil fertility use the principles of ISFM recognizing that:

- neither practices based solely on mineral fertilizers nor solely on organic matter management are sufficient for sustainable agricultural production;
- well-adapted, disease- and pest-resistant germplasm is necessary to make efficient use of available nutrients; and
- good agronomic practices in terms of planting dates, planting densities and weeding are essential to ensure efficient use of scarce nutrient resources.

In addition to these principles we recognize:

- the need to target nutrient resources within crop rotation cycles, going beyond recommendations for single crops; and
- the importance of integrating livestock within farming systems.

Despite major changes in thinking concerning sustainable development of agriculture in Africa, implementation of new ideas and approaches remains problematic. Information transfer to agricultural development workers (NGOs, extension workers) is slow and most information available from government offices in SSA countries is decades old. The diversity of local conditions in terms of economic and infrastructure development as well as agroecology suggests the need for best-fit approaches to information delivery services.

In developing guidelines, decision making can be divided into three time horizons:

- **Operational decisions** address the short-term, day-to-day management of the farm in relation to weather, crop development, livestock feeding needs and so on.
- **Tactical decisions** are concerned with the medium term, such as which crops to grow in which field in a given season, and the selection of production methods in line with the farm organization.
- **Strategic decisions** concern the long term, such as farm organization in relation to endowments of land, labour and capital for investment, and in relation to production orientation in terms of choice of crop rotations, and investment in different types of livestock.

2.5 Conclusions

In the next section we will explain what ISFM is and how it can be used to increase productivity in farming systems in SSA.

2.6 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

Andriesse, W., Giller, K.E., Jiggins, J., Löffler, H., Oosterveer, P. and Woodhill, J. (2007) The Role of Agriculture in Achieving MDG1 – a Review of the Leading Reports. 90. Wageningen International, Wageningen. Retrieved August 2012 from http://library.wur.nl/way/bestanden/clc/1860193.pdf.

> *This report gives an overview of a series of important reports concerning agriculture and the Millenium Development Goal 1 to halve hunger and poverty by 2015. Available online.*

de Koeijer, T.J., Wossink, G.A.A., van Ittersum, M.K., Struik, P.C. and Renkema, J.A. (1999) A conceptual model for analysing input–output coefficients in arable farming systems: from diagnosis towards design. *Agricultural Systems* 61, 33–44.

> *A research article that addresses the difference between operational, tactical and strategic decision making at farm level.*

Dorward, A. (2009) Integrating contested aspirations, processes and policy: development as hanging in, stepping up and stepping out. *Development Policy Review* 27, 131–146.

> *In this paper you will find an interesting description of the widely different livelihood strategies of smallholder farmers.*

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C. and Vanlauwe, B. (2011) Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems* 104, 191–203.

> *This article addresses the diversity of smallholder farming systems in Africa and discusses application of farming systems analysis to assist in targeting of ISFM technologies.*

Sanginga, N. and Woomer, P. (eds) (2009) *Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process*. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture, Nairobi, 263 pp.

> *A book on integrated soil fertility management in Africa.*

Tittonell, P., Vanlauwe, B., Misiko, M. and Giller, K.E. (2011) Targeting resources within diverse, heterogeneous and dynamic farming systems: towards a 'uniquely African Green Revolution'. In: Bationo, A., Waswa, B., Okeyo, J.M., Maina, F. and Kihara, J. (eds) *Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts*. Springer, Dordrecht, pp. 747–758.

This conference paper discusses targeting ISFM technologies to address Kofi Annan's vision of a Green Revolution that recognizes the diversity of agriculture in Africa.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E.M.A. and Woomer, P.L. (2010) Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39, 17–24.

In this article ISFM is defined and explained in detail.

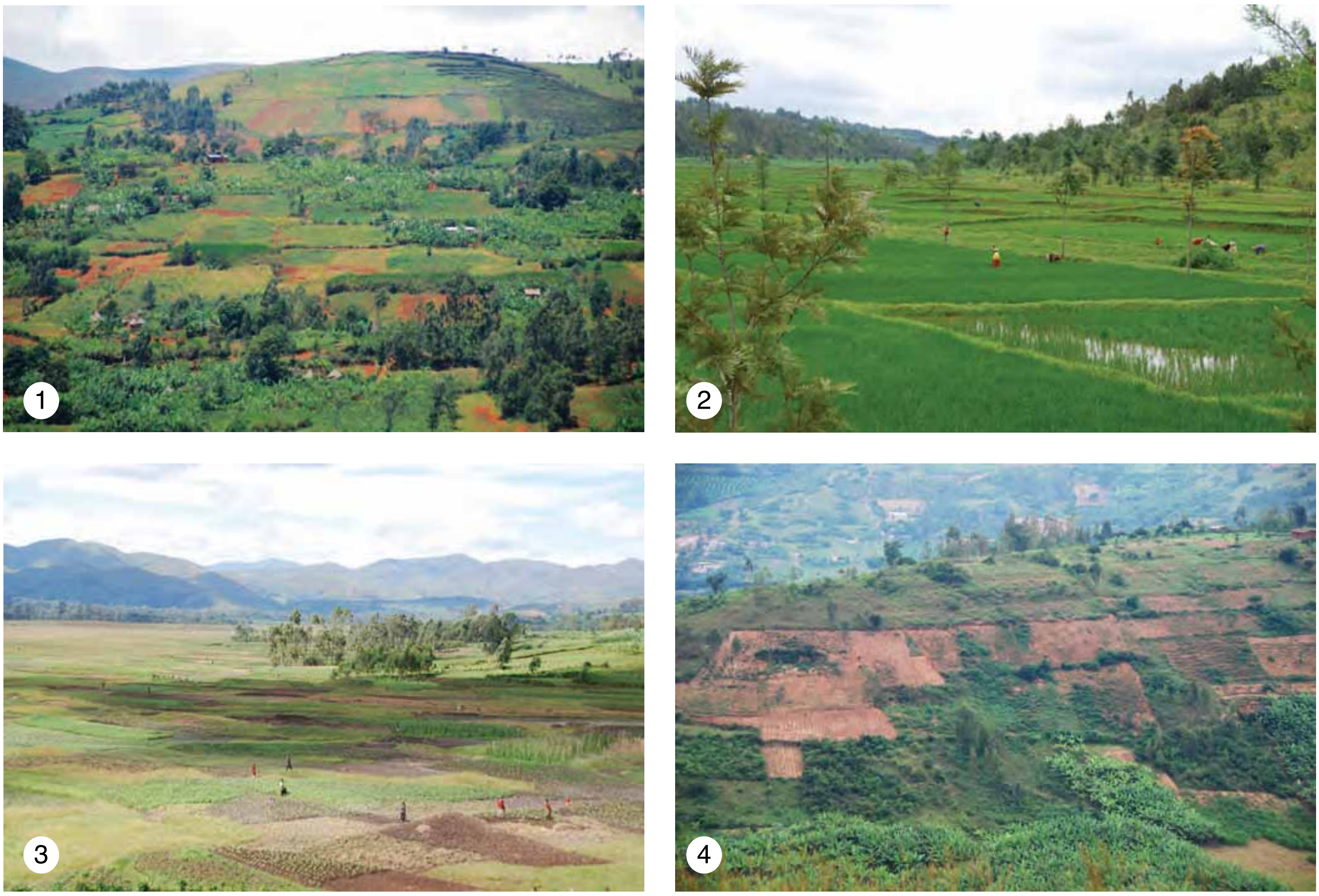


Photo 2.1 Agricultural landscapes in SSA are very diverse and workers must identify ISFM techniques that fit best with the particular area in which they are working. Farmers cultivate food crops and bananas on sloping land in the eastern part of Democratic Republic of Congo (DRC) where appropriate soil conservation is required (1). Lowland rice provides staple food and may present opportunities for market-oriented crop intensification in western Rwanda (2). A large, flat, drained valley-bottom swamp provides opportunities for subsistence crop production in western Rwanda (3). Very steep land cultivated with subsistence crops in western Rwanda where erosion is depleting the soil resource base and permanent crops might be more sustainable (4).

Photo 2.2 Large areas of degraded land in SSA could be rehabilitated and brought into production. Soil rehabilitation requires large amounts of organic residues as well as mineral fertilizer inputs to restore productivity.

Photo 2.3 Soil fertility varies greatly between fields in this farm. Different soil fertility management strategies will be required in each field and the farmer needs to manage all the fields under an overarching strategy.

3 Principles of ISFM

3.1 Introduction

In this section we describe the history of the development of integrated soil fertility management (ISFM) and how the approach has been built up based on experience gained from more than 50 years of work on soil fertility management in sub-Saharan Africa (SSA). A definition of ISFM is then provided and broken down into its component parts and some of the theory and conceptual thinking behind ISFM is explained.

Basic information on crop agronomy and soil science is provided in Section 6 for the benefit of workers without an agricultural background that are engaged in the extension of ISFM techniques.

3.2 History of approaches to soil fertility management in SSA

During the past three decades, the understanding that underpins nutrient management in cropping systems in SSA has undergone substantial change due to improved knowledge, based on extensive field research as well as changes in the overall social, economic and political environment in SSA (Table 3.1).

In the 1960s and 1970s major emphasis was placed on the use of mineral fertilizer to achieve proper crop nutrition and improved crop yields (Table 3.1). In the 1980s more emphasis was given to the use of organic resources, partly because of the problems with fertilizer access in SSA during that period.

At present much research has shown the importance of *combining* the use of mineral fertilizers and organic resources in ways that are adapted to local conditions to achieve satisfactory crop yields and efficient fertilizer use. This is the essence of ISFM.

Table 3.1 Changes in tropical soil fertility management paradigms over the past five decades.

Period	Approach	Role of fertilizer	Role of organic inputs	Experience
1960s to 1970s	External input use.	Use of fertilizer alone thought sufficient to improve and sustain yields.	Organic resources play a minimal role.	Limited success due to shortfalls in infrastructure, policy and farming systems.
1980s	Organic input use.	Fertilizer plays a minimal role.	Organic resources are the main source of nutrients.	Limited adoption. Organic matter production requires livestock ownership, excessive land and labour.
1990s	Combined use of fertilizer and organic residues.	Fertilizer use is essential to alleviate the main nutrient constraints.	Organic resources are the major ‘entry point’ to soil fertility improvement and serve other functions besides nutrient supply.	Localized adoption around specific crops.
2000s	Integrated Soil Fertility Management.	Fertilizer is a major entry point to increase yields and supply needed organic resources.	Organic resources can improve the use efficiency of fertilizer.	Goal of large-scope adoption!

3.2.1 Focus on mineral fertilizer use

Since the invention of mineral fertilizers in the 19th century until the 1980s, fertilizer use combined with improved seeds and planting materials have been the major drivers of improved productivity in agriculture. The appropriate use of external inputs (i.e. seeds, fertilizer, lime and irrigation water) has been able to sustain crop production, and increased use of mineral fertilizers has been responsible for an important share of worldwide improvement in agricultural productivity.

The use of external inputs, principally fertilizers and lime, together with the use of improved cereal varieties, irrigation and increasing the number of crops grown each year, which together is termed crop intensification, generated a 'Green Revolution' in Asia and Latin America where there have been large increases in crop yields since the 1960s.

Research and selected experience, mainly with maize, rice, grain legumes and cotton, has also shown that fertilizer has the potential to be a powerful tool for enhancing productivity in SSA. In the past, some farmers became frustrated with fertilizer use, however, because fertilizer recommendations were insufficiently tailored to the farmer's particular circumstances:

- We now know that in densely populated areas with limited access to organic resources, soil fertility varies widely within each farm. For example, there may be more fertile fields close to the farmer's house and less fertile soils in more distant fields.
- The farmer's social and economic situation needs to be taken into account when devising fertilizer recommendations. For example, market-oriented farmers are strongly engaged in the production of crop products for sale while other farmers, usually less well endowed with production resources (land, labour, cash), are less market oriented and instead seek to ensure food self-sufficiency.

Failure to address directly the farmers' goals and take into account their operating environment often led to disappointing results with fertilizer use in the 1980s and 1990s.

Farmers often considered fertilizers to be 'too costly' or 'unaffordable', particularly when fertilizer prices increased following the removal of fertilizer subsidies. Up to the present, fertilizer is more costly in most countries in SSA than in any other continent in the world, mainly because of the lack of efficient fertilizer market infrastructure and poor transport networks.

To some extent, fertilizer use in SSA has been affected by concerns in Europe and North America and parts of Asia where excessive use of mineral fertilizers has sometimes caused undesirable environmental impacts. Some policy makers fear that increased use of fertilizer might lead to similar problems in SSA. At present, however, fertilizer application rates in SSA are very small (5–10 kg/ha), far below the target of 50 kg/ha set by the Abuja Declaration (Box 3.1) and up to ten times smaller compared with application rates in regions more economically developed than SSA.

Box 3.1 The Abuja Declaration

The **Abuja Declaration** was issued as a result of the Africa Fertilizer Summit, held in Abuja, Nigeria, in June 2006. The Declaration included the following objectives:

- Increase the level of use of fertilizer nutrients from the current average of 8 kg/ha to an average of at least 50 kg/ha by 2015.
- Reduce the cost of fertilizer procurement at national and regional levels.
- Improve farmers' access to fertilizers by developing and scaling up input dealers and community-based networks across rural areas.
- Address the fertilizer needs of farmers, especially women, and develop and strengthen the capacity of youth, farmers' associations, civil society organizations and the private sector.
- Improve farmers' access to fertilizer by granting targeted subsidies in favour of the fertilizer sector, with special attention to poor farmers.

The results of long-term agronomic trials in various countries show that soil may become depleted of some nutrients when fertilizer use is unbalanced, for example, when large amounts of nitrogen fertilizers are applied without the required amounts of fertilizers containing P, K and other nutrients. These problems can be corrected or prevented, however, by ISFM.

During the 1990s, results of research and experience showed that the ecological and agronomic concerns about fertilizer inputs can be eliminated through their judicious use in combination with organic inputs (straw, compost, fallow legumes), and locally available soil amendments such as reactive phosphate rock and lime. Much effort followed to identify approaches to generate the necessary organic inputs required, using technologies based on agroforestry and the use of herbaceous legumes (e.g. cover crops) or dual-purpose grain legumes (e.g. long-duration soybeans).

In some places, perhaps the most significant concern regarding fertilizer use is its poor performance in hostile environments where top soil has been lost due to soil erosion and surface water runoff and stocks of nutrients, other than those supplied as fertilizer, have been depleted due to lack of nutrient replenishment, rendering soils less responsive to fertilizer inputs. In addition, other factors such as drought, weed infestation and soil acidity and alkalinity often make fertilizer use uneconomic due to poor fertilizer nutrient uptake and conversion into crop products.

These are some of the factors that have led researchers to endorse the *combined* use of fertilizers and organic materials (crop residues and animal manures) to improve crop productivity and agronomic efficiency.

3.2.2 The use of low-input methods for soil fertility improvement

Low External Input Sustainable Agriculture (LEISA) and other so-called 'low-input' strategies have been promoted by some donors and NGOs in response to some of the problems discussed above and the high cost of fertilizer. In the LEISA approach it is assumed that organic resources are available in sufficient quantity to improve productivity and sustain the natural resource base. Legume crops, trees and shrubs may add significant amounts of N by biological N_2-fixation, and deep-rooting trees recycle to the soil surface nutrients taken up from below the rooting depth of annual crop plants. In most cases, however, the use of organic inputs such as manure and compost is part of an *internal* flow of nutrients within farms and, therefore, does not result in any net addition of nutrients to the farm.

Conserving nutrients is clearly important but if the nutrient capital within the farm system is insufficient, yields stagnate and farmers are trapped in a downward spiral of decreasing nutrient stocks and declining yields (Figure 3.1). In response, the farmer is forced to expand the area under cultivation to achieve his/her production goals. At the same time, agronomic trials show that there are often large increases in crop yields when nutrients are *added* to the farm system. It has also been found that the *quality* of organic resources is often poor and the *quantity* of manure or other organic materials is simply insufficient to meet the nutrient demand of crops. Organic materials generally contain small amounts of nutrients compared with mineral fertilizers and are therefore more costly to store, transport and apply.

For example, in livestock systems in West Africa, current average application rates of manure are very small (0.5–2.0 t/ha) and the potential transfer of nutrients in animal manure to crop fields is therefore only about 2.5 kg N and 0.6 kg P/ha of cropland and insufficient to meet crop requirements.

Despite its vital role in sustaining soil fertility, the *quantity* of manure needed is often simply not available because there are not sufficient animals to provide the manure required, particularly when drought results in a decrease in the number of farm livestock because of fodder shortages. Farmers can increase their numbers of livestock only if they have sufficient grazing land or if they are able to provide sufficient fodder, which in turn requires increased productivity of crops to generate sufficient amounts of crop residues and animal fodder.

Similarly, while the preparation of compost from straw is often advocated, farming systems analysis clearly shows that there are many competing uses for straw. For example, where straw is required for use as animal feed little can be spared for the preparation of compost.

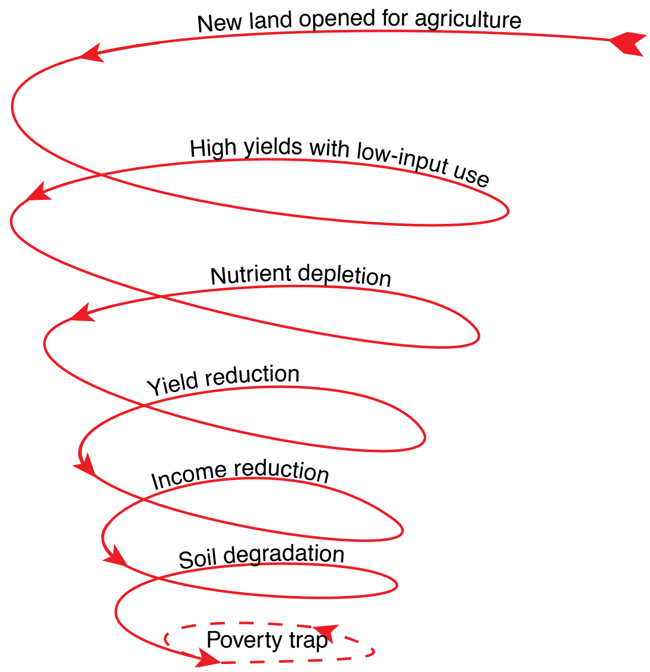


Figure 3.1 The downward spiral to the poverty trap for farm systems where the nutrients added are insufficient to maintain soil fertility.

It is possible to produce organic inputs by planting cover crops (e.g. *Mucuna pruriens*) and other plants, whether on-farm or off-farm for use as soil amendments. While promising results have been obtained in researcher-controlled agronomic trials, farmers seldom adopt such practices because they are: (i) labour intensive; (ii) cannot provide sufficient nutrients to sustain productivity; and (iii) do not yield products that can be either eaten or sold in the market. Cultivation of cover plants on poor soils is, in essence, only recycling poverty.

These are some of the reasons that sustaining soil fertility and increasing productivity using organic resources *alone* have proved to be impractical. All the scientific evidence indicates that on SSA's depleted soils, production cannot be increased without bringing to the farm nutrients from outside either through livestock manure or mineral fertilizer.

3.2.3 Towards the integration of fertilizer and organic resource use

The ISFM strategy uses the same basic principles but has changed the focus from *seeking* organic resources to the use of fertilizer to *generate* the required organic resources in the form of crop residues or manure derived from crop production (Table 3.1). Agronomic research over the past 20 years points to the need to combine both organic resources and mineral fertilizers to increase soil fertility, improve crop yields and improve farmers' livelihoods. These are some of the arguments behind the Abuja Declaration of 2006 (Box 3.1).

3.3 Definition of ISFM

ISFM may be defined as:

> A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at optimizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic and economic principles.

The process is described in terms of interventions, outputs, outcomes and impact in Figure 3.2.

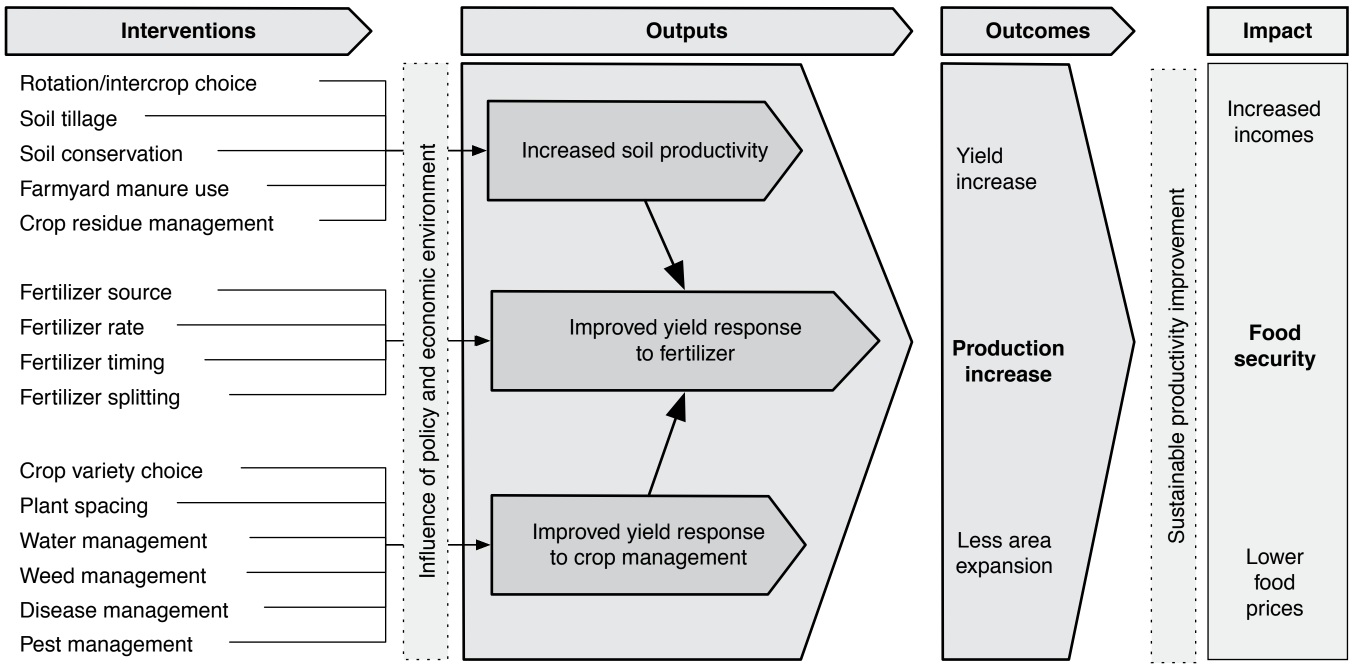


Figure 3.2 ISFM involves the combined use of appropriate interventions on soil management, fertilizer use and crop agronomy to drive the main outputs of increased yield and productivity. The introduction of interventions is affected by market economics and government policy. When introduced successfully, productivity is increased and less land is required to achieve a given level of production. The impact is the sustainable improvement of food security, increased farm incomes and lower food prices, which benefit the urban population.

This definition combines all the agronomic components necessary to make crops grow and yield well, including the use of high yielding and healthy planting material, plant nutrients, whether supplied as organic materials or mineral fertilizers, and other soil amendments.

The ISFM approach embraces the principles of plant production ecology where yield is a function of the interaction between genotype, environment and management:

$$\text{Yield} = \text{G (genotype)} \times \text{E (environment)} \times \text{M (management)}$$

where:

- **G**enotype is the seed or plants used in the farming system. They may be local or improved varieties.
- **E**nvironment refers to the soils and climate in the particular location.
- **M**anagement refers to the farmer's ability and skill in managing crops and the farming system.

We will now use some diagrams or models to explore the effect of ISFM on fertilizer use efficiency and yield.

A model can be used to illustrate the impact of moving towards more complete implementation of ISFM (Figure 3.3):

- The more complete the implementation of ISFM the greater the value for agronomic efficiency.
- We make a distinction between responsive soils and less responsive soils:
  - The response to seed and fertilizer inputs is large in responsive soils (point A).
  - The response to seed and fertilizer inputs is small in non-responsive 'degraded' soils (point B) and organic resources are required to make efficient use of fertilizer and improved seeds (point C).

Full implementation of ISFM requires knowledge on how to adapt practices to each farm's constraints and opportunities. We will now explain what each part of the definition of ISFM means.

Another model can be used to explain the interactions between different ISFM components (Figure 3.4):

- The response to fertilizer is greater when fertilizer is applied with added organic resources (e.g. animal manure) (line A) and the response is even greater at higher rates of fertilizer input (line B).
- The impact of animal manure on response to fertilizer depends on the amount of manure added.
- A much larger amount of fertilizer is required to reach yield at line C when no organic matter is used (line A) compared with the use of mineral fertilizer in combination with organic matter (line B).

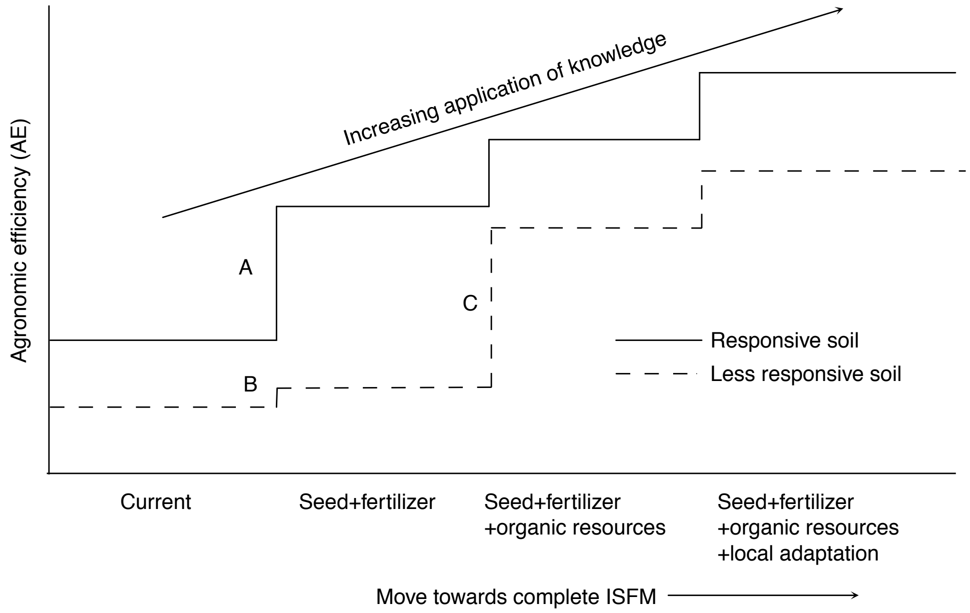


Figure 3.3 Relationship between the agronomic efficiency (AE) of fertilizers and organic resource and the implementation of various components of ISFM.

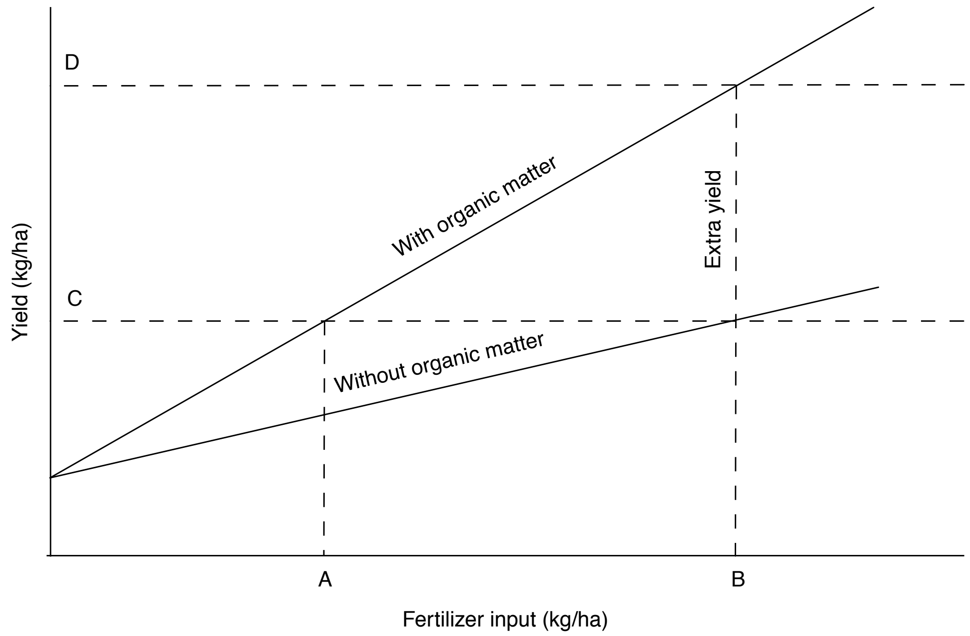


Figure 3.4 Positive interaction between fertilizer and organic inputs resulting in extra yield due to ISFM practices.

When two components used in combination result in a greater yield than the two components implemented separately we call this synergy a ‘positive interaction’. The extent to which farmers realize these positive interactions will depend on the relative costs of organic resources and fertilizer. A farmer with easy access to manure will likely opt to use a combination of manure and fertilizer while a farmer without access to manure will have to use more fertilizer. This decision is an example of what we call ‘local adaptation’ and illustrates the point that economic analysis should shape ISFM choices.

3.3.1 Use of mineral fertilizers

Mineral fertilizers are required to supplement the nutrients recycled or added in the form of crop residues and animal manures. Fertilizers are concentrated sources of essential nutrients in a form that is readily available for plant uptake. They are often less costly than animal manures in terms of the cost of the nutrients that they contain (i.e. $/kg nutrient) but often viewed as more costly by farmers because they require a cash outlay.

ISFM places great emphasis on using mineral fertilizers on fields in the farm where they will provide the greatest beneficial effect.

3.3.2 Use of organic inputs

Organic inputs (crop residues and animal manures) are also an important source of nutrients, but their N, P, Mg and Ca content is only released following decomposition. By contrast, K is released rapidly from animal manures and crop residues because it is contained in the cell sap. Further, the amount of nutrients contained in organic resources is usually insufficient to sustain required levels of crop productivity and realize the full economic potential of a farmer’s land and labour resources.

In addition to supplying nutrients, organic inputs also contribute to crop growth in other ways by:

- increasing the crop response to mineral fertilizer;
- improving the soil’s capacity to store moisture;
- regulating soil chemical and physical properties that affect nutrient storage and availability as well as root growth;
- adding nutrients not contained in mineral fertilizers;
- creating a better rooting environment;
- improving the availability of phosphorus for plant uptake;
- ameliorating problems such as soil acidity; and
- replenishing soil organic matter.

In ISFM we emphasize the importance of optimizing the use of organic resources after exploring their opportunity cost (e.g. comparing the retention of organic resources in the field with their use for livestock feed, mulch or compost production).

3.3.3 Use of improved germplasm

It is important that the farmer uses the crop planting materials (usually seed but sometimes seedlings) best adapted to the particular farm in terms of:

- responsiveness to nutrients (varieties differ in their responsiveness to added nutrients);
- adaptation to the local environment (soils, climate); and
- resistance to pests and diseases (unhealthy plants do not take up nutrients efficiently).

Improved germplasm usually has a higher harvest index (HI) (the ratio of crop product to total biomass production) because more of the total biomass production is converted into the harvested product than in unimproved varieties. Improved legume varieties with a lower HI are sometimes selected, however, because they can be treated as 'dual-function' crop plants. For example, multi-purpose soybean varieties used for food, feed and soil fertility improvement provide a large biomass that benefits the next crop in the rotation in addition to an acceptable grain yield.

Farmers should be informed of promising new varieties that have been tested and released for use in their locality.

3.3.4 Effect of combining the use of fertilizer, organic inputs and germplasm

We will now use three examples to illustrate the importance of considering the interactions that occur between fertilizer, organic input and germplasm use.

Yield improvement is usually greater when organic inputs and fertilizers are applied together. For example, in Sadore, Niger, the yield of millet was increased by about 1.0 t/ha by adding crop residues and by 1.5 t/ha by adding fertilizers (Figure 3.5). When fertilizers and crop residues were applied together, the yield increase was larger and yields increased progressively over the long term.

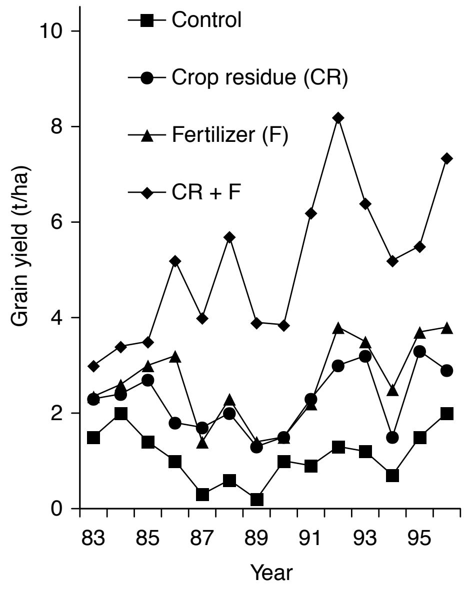


Figure 3.5 Long-term effect of fertilizer and crop residues on millet grain yield in Sadore, Niger.

The effect of crop nutrition and improved germplasm is illustrated by the effect of fertilizers on the yield of local and improved open-pollinated maize varieties in South Kivu, DRC (Figure 3.6). In this example maize grain yields from two local (Kasai and Kuleni) and two improved open-pollinating (BH140 and BH540) maize varieties were compared when grown with and without fertilizer. Fertilized crops received 60 kg N, 13 kg P and 25 kg K/ha applied as compound NPK fertilizer (17–17–17) and urea (46% N) in split basal and top-dressed applications.

We can learn a number of important lessons from this trial:

- The largest yield was obtained with fertilized hybrids.
- Both local varieties produced larger yields when fertilized compared with the unfertilized BH140. So applying fertilizer to local varieties can result in significant yield gains.
- Local and improved varieties produced larger grain yields when fertilizer was applied and the yield increase was similar in the local varieties and BH540. The greatest response to fertilizer was obtained with variety BH140. BH540 was not more responsive to fertilizer than the two local varieties.
- Yields were more than doubled from 2.6 t/ha (Kasai variety without fertilizer) to 6.0 t/ha (BH540 variety with fertilizer) when both fertilizer and improved germplasm was used.
- The yield from unfertilized variety BH540 was slightly greater than the two local varieties with fertilizer application.
- Economic analysis would be required to identify the most profitable combination of planting material and fertilizer application.

These varieties might respond very differently to the same treatments in a different locality, so it is best to avoid making generalizations based on the results of a single trial. For example, contrary to the results of this trial, improved varieties often are more responsive than local varieties to fertilizer application.

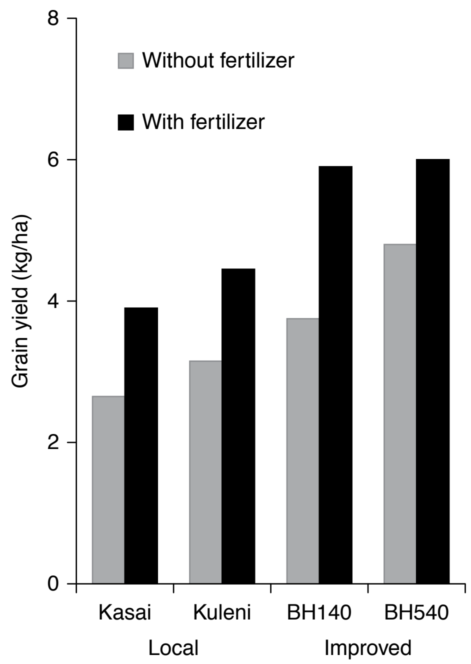


Figure 3.6 Effect of fertilizer on maize grain yield from two local and two improved maize varieties in South Kivu, DRC.

It is important to consider response to fertilizer inputs when selecting varieties for a particular location (Figure 3.7). In this example the grain yield of different soybean varieties was compared with and without the addition of P fertilizer. Some varieties were low yielders (e.g. point a) while others yielded well but did not respond to P fertilizer (e.g. point b). A cluster of varieties yielded well and gave a good response to P fertilizer and was selected for further testing in farmers' fields (point c).

Finally, we must also consider the effect of farm management on the response to inputs (Figure 3.8). In this example there was a large effect on crop yield and response to fertilizer by improving aspects of crop management such as planting date, and density and timing of P fertilizer application. The better the crop management, the greater the response to fertilizer (Figure 3.8).

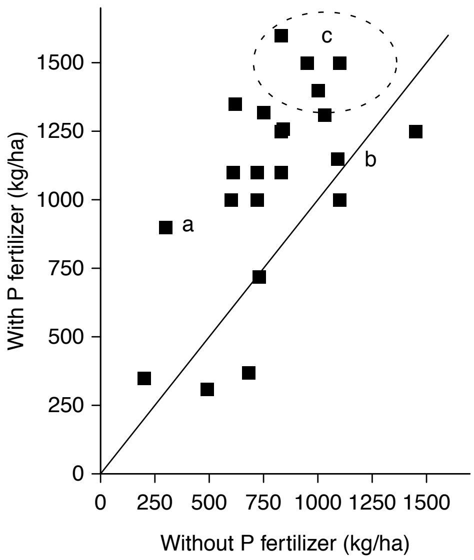


Figure 3.7 Response of different soybean varieties to phosphorus fertilizer.

3.3.5 Importance of local adaptation

The definition of ISFM emphasizes the need for 'local adaptation' because we need to take into account **variability**:

- between farms, in terms of farming goals, and objectives, size, labour availability, ownership of livestock, importance of off-farm income; and
- in the amount of production resources (i.e. land, money, labour, crop residues and animal manures) that different farming families are able to invest in the fields in their farm.

The ISFM definition places emphasis on the importance of using often scarce resources like fertilizer and organic inputs efficiently while reaching economic goals that are achievable for each farm household.

We can often distinguish three kinds of soils in farmers' fields (Figure 3.9):

- Poorly responsive fertile 'in-fields' are often found close to the farmer's house and have benefitted over the years from inputs such as household waste, crop residues, animal manures and sometimes human waste.
- Responsive 'out-fields' are often found some distance from the farmer's house where crop residues and animal manures have not been applied.
- Poorly responsive 'bush-fields' are also found at a greater distance from the farmer's field and have become degraded, perhaps because they are under communal use and farmers are reluctant to invest in soil fertility improvement because they are unsure of whether they will be able to grow crops on the land in the future.

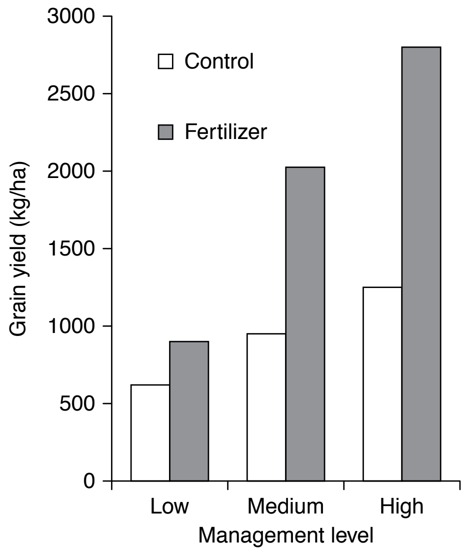


Figure 3.8 Effect of agronomic management on response to fertilizer.

Thus, local adaptation also refers to the need to take into account differences in the responsiveness of soils:

- Only small amounts of fertilizer are required to replenish nutrient stocks and maintain the fertility of fertile fields.
- For responsive soils, fertilizer recommendations should be targeted to each field based on anticipated or proven responses. The recommendation should also include soil amendments and other soil fertility management practices (e.g. organic inputs) required to achieve a full response.
- Non-responsive soils often have complex and less understood sets of constraints to crop production. Rehabilitation should only be carried out where solutions have been developed and tested and have been found to be practical and economical.

Response to fertilizer and the addition of large amounts of cattle manure was measured in responsive in-fields and non-responsive out-fields in Zimbabwe (Figure 3.10). Response to fertilizer in the in-fields was not improved by the addition of crop residues but there was a marked increase in the response to fertilizer after 3 years during which time large amounts of crop residues were added to the soil.

Another point emphasized in ISFM is the importance of identifying ‘entry points’ where ISFM components can be introduced and will produce a large return for the farmer to input use or changes to production practices. Farming systems analysis (FSA) is carried out to identify and prioritize entry points:

- Which parts of the farming system should be prioritized for improvement?
- What will be the impact of improvements in the prioritized part of the farming system on other farming system components?

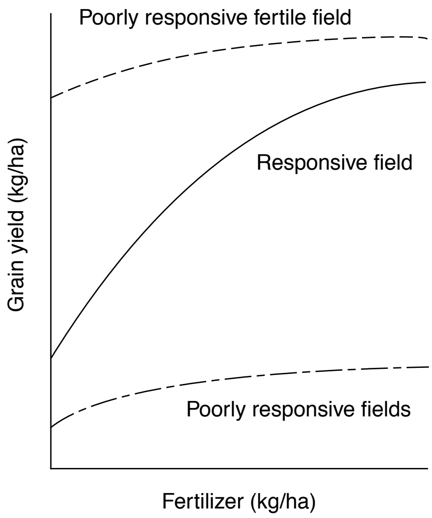


Figure 3.9 Fertilizer response in poorly responsive fertile soils, poorly responsive infertile soils and responsive fields.

3.3.6 Optimizing agronomic efficiency

The saying ‘you can only manage what you measure’ is apt in the context of ISFM. We use the term ‘agronomic efficiency’ (AE) to measure the amount of additional yield obtained per kilogram of nutrient applied.

AE is defined as incremental return to applied inputs, or:

$$\text{AE - X (kg grain/kg nutrient X)} = \frac{(Y_F - Y_C)}{X_{appl}}$$

where:

- Y_F and Y_C refer to yields (in kg/ha) following treatment where nutrients have been applied (Y_F) and in the control plot (Y_C).
- X_{appl} is the amount of nutrient X applied (kg nutrient/ha) from fertilizers and organic inputs.

In other words, the AE of applied nutrients is equal to the additional crop yield obtained with the application of nutrients (i.e. the yield in the treatment with fertilizer minus yield in the treatment without fertilizer) divided by the amount of nutrients applied (in kilograms per hectare).

Note that we use the amount of nutrients and not the amount of fertilizer applied in the calculation.

The ISFM definition focuses on maximizing the AE of nutrients from fertilizer and organic inputs since these are both scarce resources in the areas where agricultural intensification is needed.

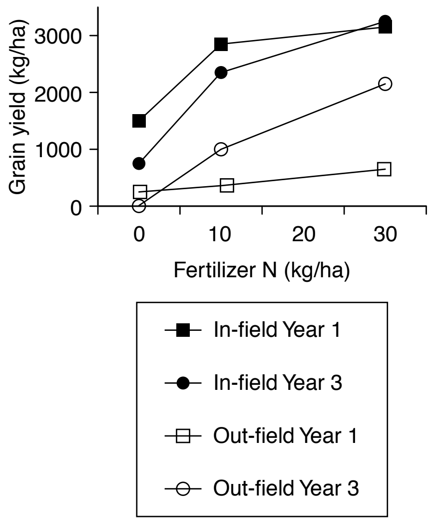


Figure 3.10 Response to N fertilizer and farmyard manure over time in responsive in-fields and initially unresponsive out-fields in Zimbabwe.

It is important to keep in mind two points:

First, for a particular value of nutrient inputs (F_{appl}) there is a linear relationship between AE and crop yield (Figure 3.11). In other words, for a given nutrient application rate, a higher value of AE gives higher crop yields. For example:

- If Y_F is 3000 kg/ha, Y_C is 2000 kg/ha (yield gain 1000 kg/ha), and the amount of nutrients applied (F_{appl}) is 50 kg/ha, AE is 20 kg grain/kg nutrient (point a, Figure 3.11).
- If Y_F is 5000 kg/ha, Y_C is 2000 kg/ha (yield gain 3000 kg/ha), and the amount of nutrients applied is 50 kg/ha, AE is 60 kg grain/kg nutrient (point b, Figure 3.11).

- If Y_F is 7000 kg/ha, Y_C is 2000 kg/ha (yield gain 5000 kg/ha), and the amount of nutrients applied is 50 kg/ha, AE is 100 kg grain/kg nutrient (point c, Figure 3.11).

There are many ways to increase AE, and therefore yield, at a particular application rate of fertilizer:

- Apply fertilizer nutrients at the right time (i.e. when they are required to maximize vegetative growth and yield).
- Apply fertilizer nutrients in the right place (i.e. where the plant can access the fertilizer nutrients and nutrient uptake is maximized).
- Apply fertilizer in several split applications in order to reduce the amount of fertilizer nutrients lost due to leaching.
- Plant the crop at the right planting density so that there are enough plants to ensure maximum yield response but not so many that inter-plant competition becomes a problem.

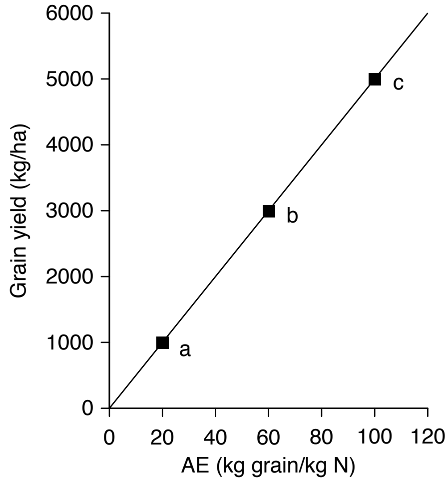


Figure 3.11 Relationship between agronomic efficiency of N use (AE-N) and grain yield at a particular fertilizer rate (50 kg N/ha).

Second, we use the term value:cost ratio (VCR) to make an assessment of the economics of fertilizer application by comparing the value of *additional* yield with the *cost* of the inputs required to achieve the yield increase:

$$VCR = \frac{\text{Extra grain produced (kg)} \times \text{Value of produce (\$/kg)}}{\text{Inputs applied (kg)} \times \text{Cost of inputs (\$/kg)}}$$

A typical response curve to applied fertilizer shows a steep linear response at lower rates of fertilizer application (i.e. 0–50 kg/ha) (Figure 3.12). As the rate of fertilizer application increases from 50 to 250 kg N/ha the rate of response decreases and reaches a plateau, in this case at about 6000 kg/ha.

If we use the response curve to calculate AE, we can see that in this example there is an initial part where AE is at a constant and maximum value of about 70 kg grain/kg N (Figure 3.12). As the response curve moves towards the plateau, the value of AE decreases reaching a low point of 20 kg grain/kg N applied.

In other words, when applying very large amounts of nutrient inputs, AE is reduced to low values. In smallholder agriculture in SSA, however, most farms apply fertilizers within the linear part of the response function (i.e. in this example <100 kg N/ha) and therefore achieve quite high AE, provided sound agronomic principles are applied in the field.

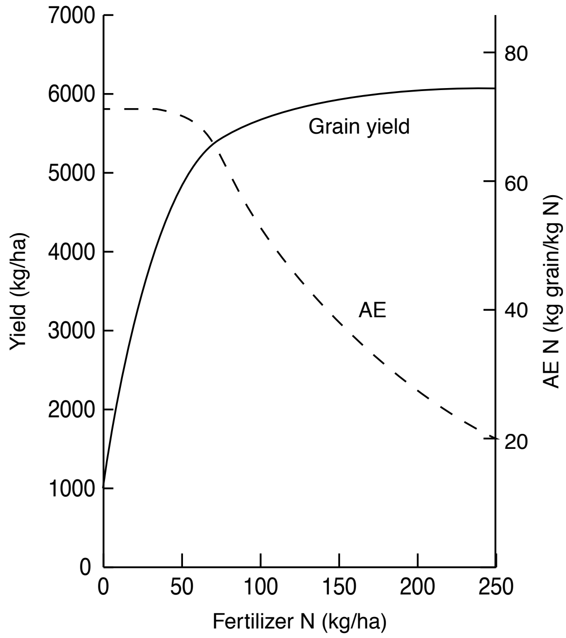


Figure 3.12 Diagram to show the conceptual relationship between fertilizer application rate, yield and agronomic efficiency (AE).

3.3.7 Sound agronomic principles

The ISFM approach assumes that proper crop management practices are used to achieve the maximum return to investments in the germplasm and nutrients used. Good crop management includes the use of appropriate varieties, appropriate land preparation, spacing, planting dates and practices, weeding, pest and disease management practices, and eventually appropriate intercropping arrangements.

Land equivalent ratio (LER)

We are often faced with the question of whether it is better for the farmer to grow two crops in an intercrop or to grow them separately. The term land equivalent ratio (LER) is used to evaluate the productivity of intercrops compared with monocrops. The LER is defined as the area needed under monocropping of each crop to produce the same yield as 1 ha of the same crops grown in an intercropping system.

LER is calculated as:

$$\mathrm{LER} = \sum \left(\frac{Yi_i}{Ym_i} \right)$$

where:

- Yi_i is the yield of each crop or variety in the intercrop.
- Ym_i is the yield of each crop or variety in the monocrop.

An LER >1 means that a larger area would be needed to produce the same yields when the crops are planted as monocrops compared with intercrops. In such instances, intercrops give relatively better yields when compared with the performance of the same crops in monocropped systems.

3.3.8 Sound economic principles

A model can be used to explain the impact of ISFM on the response to nutrients in terms of grain yield and profitability (Figure 3.13):

- Response 1 and Response 2 represent the grain yield response to added nitrogen fertilizer in a farmer's field. Response 2 is greater than Response 1 because of the effect of other ISFM components on the response to N fertilizer (e.g. splitting and timing of fertilizer application, and use of germplasm that is more responsive to fertilizer).
- The farmer can move from point A to point B by adopting factors that improve response to fertilizer N (e.g. splitting and timing of application, use of more responsive germplasm, improved plant population).
- The farmer can increase grain yields and profits by increasing the N fertilizer application rate in addition to improved splitting and timing of N fertilizer application (e.g. moving from point B to point C).

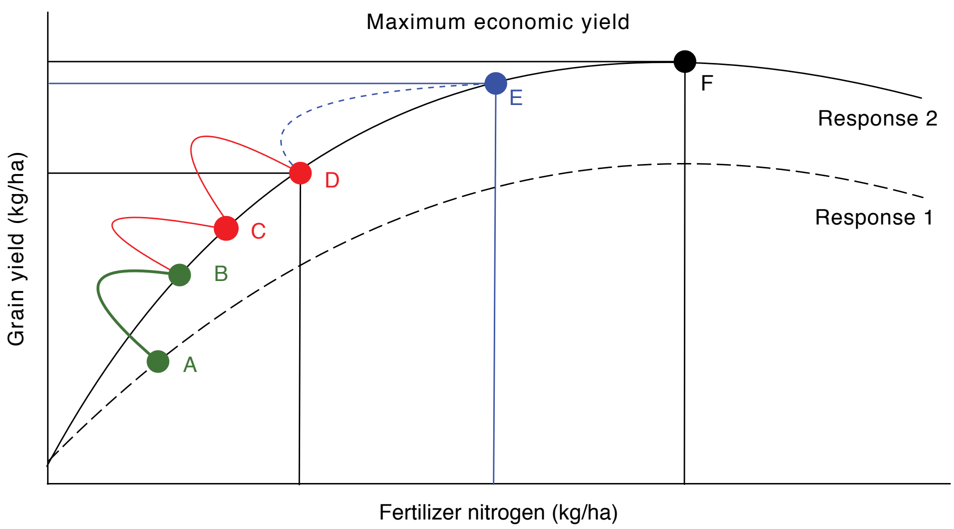


Figure 3.13 Relationship between nitrogen application rate and grain yield.

- Point F is the maximum *agronomic* yield and point E the maximum *economic* yield, which is determined by the ratio of N fertilizer price to grain price and the shape of the response curve.
- The farmer can increase grain yields and profits by further increases in N fertilizer application rates up to the point of maximum economic yield (e.g. moving from point C to point D), but with each incremental application of fertilizer the return in kilograms of output per kilogram of fertilizer used decreases, so moving to the maximum economic yield may be viewed by some farmers as too risky.
- There is a range of fertilizer use in which agronomic efficiency (AE) is declining but still acceptable and economic returns are positive (i.e. between points B and D). The best position for the farmer between these points depends on a range of farm-specific factors.
- Moving from point E to point F is not economic because the additional income from increased crop yield is not greater than the cost of the extra increment of fertilizer use!

3.4 Conclusions

ISFM contributes to sustainability because the agronomic and soil fertility management practices sustain soil fertility by:

- focusing on efficient nutrient use (measured as AE);
- minimizing the loss of indigenous and added nutrients by the use of appropriate soil conservation techniques; and
- improving soil fertility across the farmscape.

In this section we have reviewed a definition and explored the principles of ISFM.

The goal is to change the downward spiral of declining soil fertility and crop yields (Figure 3.1) into an upward spiral where soil fertility and crop yields are increased by the combined use of organic resources and mineral fertilizer (Figure 3.14).

In the next section we will discuss practical soil fertility management practices in detail.

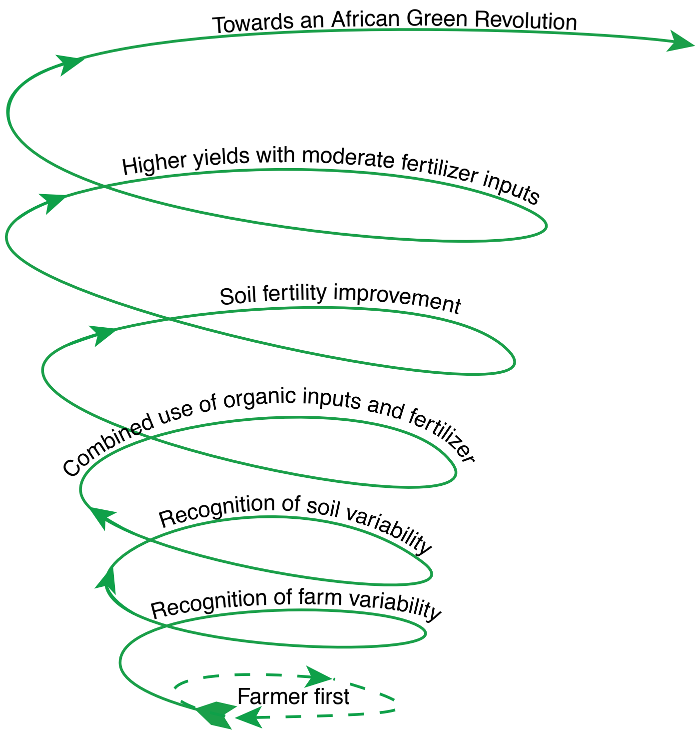


Figure 3.14 The downward spiral of soil fertility decline shown in Figure 3.1 can be reversed by careful implementation of the components of ISFM.

3.5 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

Africa Union (2006) Abuja Declaration on Fertilizer for an African Green Revolution. Africa Union, Addis Ababa. Retrieved August 2012 from http://www.nepad.org/foodsecurity/knowledge/doc/1815/abuja-declaration-fertilizer-african-green-revolution.

The Abuja Declaration is available online.

Bationo, A. (2008) *Integrated Soil Fertility Management Options for Agricultural Intensification in the Sudano-Sahelian Zone of West Africa*. Academy Science publishers, Nairobi.

A book on integrated soil fertility management in the Sudano-Sahelian zone in West Africa.

Bationo, A., Waswa, B., Okeyo, J., Maina, F. and Kihara, J. (eds) (2011) *Innovations as Key to the Green Revolution in Africa – Exploring the Scientific Facts*. Springer, Dordrecht, 1363 pp.

Papers from a symposium to assess the potential and feasibility of external input and improved soil and crop management to achieve an African Green Revolution.

Bationo, A., Waswa, B., Okeyo, J., Maina, F., Kihara, J. and Mokwunze, U. (eds) (2011) *Fighting Poverty in Sub-Saharan Agriculture: the Multiple Roles of Legumes in Integrated Soil Fertility Management*. Springer, Heidelberg, 246 pp.

A collection of papers on the multiple roles of legumes in integrated soil fertility management.

Dudal, R. (2002) Forty years of soil fertility work in sub-Saharan Africa. In: Vanlauwe, B., Diels, J., Sanginga, N. and Merckx, R. (eds) *Integrated Plant Nutrient Management in sub-Saharan Africa: From Concept to Practice*. CAB International, Wallingford, UK, pp. 7–21.

This gives an historical overview of soil fertility research in sub-Saharan Africa.

Giller, K.E., Rowe, E., de Ridder, N. and van Keulen, H. (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. *Agricultural Systems* 88, 8–27.

This article introduces and discusses the linkages between soil fertility status and resource use efficiency, including attention to soil fertility gradients and degraded, non-responsive soils.

Lövenstein, H., Lantinga, E., Rabbinge, R. and van Keulen, H. (1995) Principles of production ecology: text for course F300-001. 121. Department of Theoretical Production Ecology, Wageningen Agricultural University, Wageningen. Retrieved August 2012 from http://www.pame.wur.nl.

The principles of production ecology are explained in detail in the web-based undergraduate level course. This is an introductory BSc-level course and is available online.

Tian, G., Ishida, F., Keatinge, D., Carsky, R. and Wendt, J. (eds) (2000) *Sustaining Soil Fertility in Africa*. Soil Science Society of America, Madison, Wisconsin, 321 pp.

A collection of papers on soil fertility management in West Africa.

Tittonell, P. and Giller, K.E. (2012) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. *Field Crop Research* (in press).

Figure 3.9 is presented and discussed in this article.

Tittonell, P., Zingore, S., van Wijk, M.T., Corbeels, M.C. and Giller, K.E. (2007) Nutrient use efficiencies and crop responses to N, P and manure applications in Zimbabwean soils: exploring management strategies across soil fertility gradients. *Field Crops Research* 100, 348–368.

Together with Zingore et al. *(2007) this paper discusses the origin of soil fertility gradients and their importance in relation to agronomic efficiency of fertilizers and organic manures.*

Tittonell, P., Vanlauwe, B., Corbeels, M. and Giller, K.E. (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil* 313, 19–37.

This paper highlights the linkages between soil fertility gradients, crop management and agronomic use efficiency of nutrients in maize as indicated in Figure 3.8.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E.M.A. and Woomer, P.L. (2010) Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39, 17–24.

In addition to defining ISFM, this article explains the main ISFM concepts and is the source of Figures 3.3 and 3.4.

Zingore, S., Murwira, H.K., Delve, R.J. and Giller, K.E. (2007) Soil type, historical management and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on African smallholder farms. *Field Crops Research* 101, 296–305.

As the source of Figure 3.10, together with Tittonell et al. *(2007) this paper discusses the origin of soil fertility gradients and their importance in relation to agronomic efficiency of fertilizers and organic manures.*

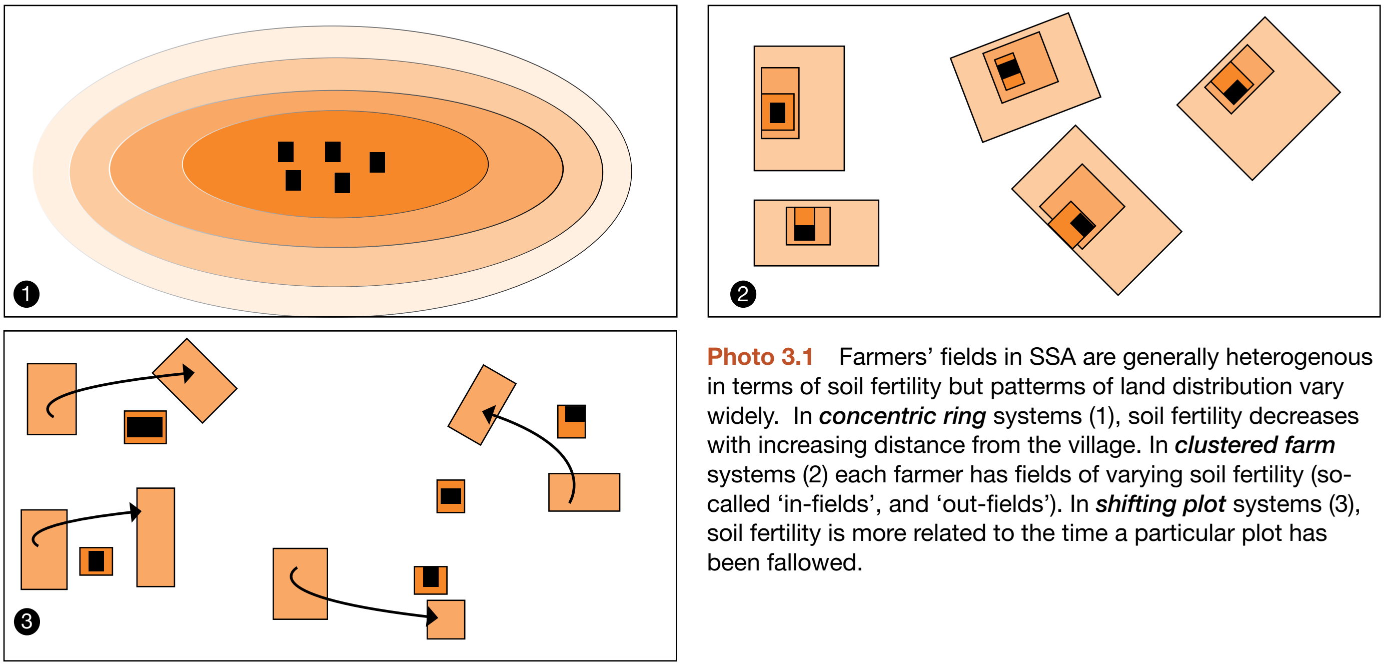


Photo 3.1 Farmers' fields in SSA are generally heterogenous in terms of soil fertility but patterms of land distribution vary widely. In ***concentric ring*** systems (1), soil fertility decreases with increasing distance from the village. In ***clustered farm*** systems (2) each farmer has fields of varying soil fertility (so-called 'in-fields', and 'out-fields'). In ***shifting plot*** systems (3), soil fertility is more related to the time a particular plot has been fallowed.

Photo 3.2 In general we can identify three classes of soil in individual farm holdings in terms of response to mineral fertilizer – 'responsive', 'less-responsive' and 'unresponsive' soils. In-fields are usually less responsive because they have benefitted from past application of household waste, crop residues and animal dung. In this particular farm in Western Kenya, however, the in-field (1) responded well to mineral fertilizer while the out-field (2) was less responsive partly due to the problem of very persistent couch grass infestation (3).

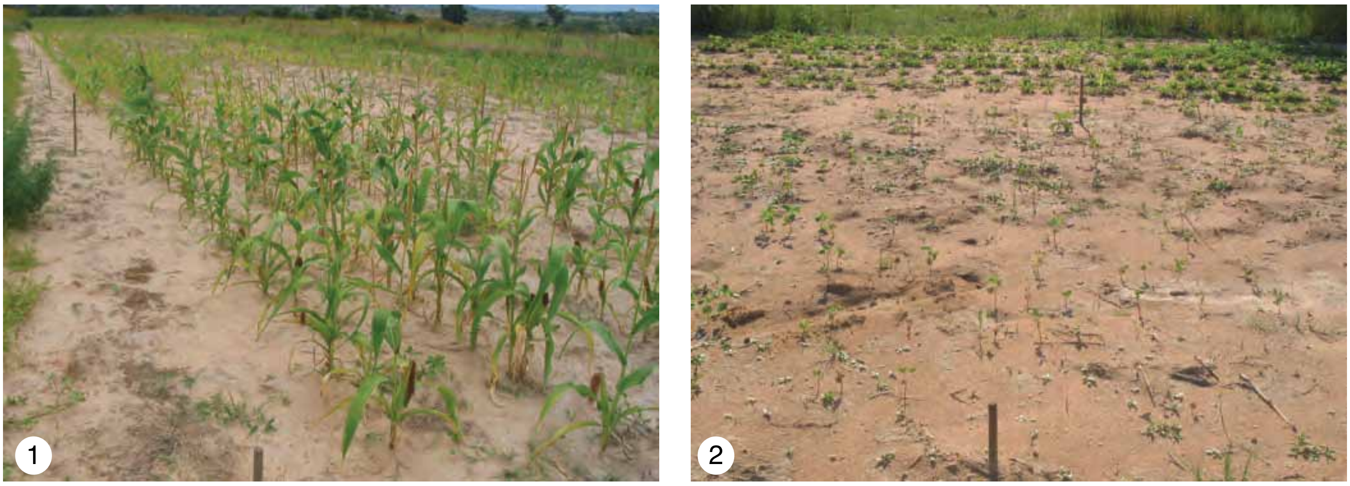


Photo 3.3 Poor response of maize (1) and legumes (2) to fertilizer in degraded soils. Large amounts of organic residues must be applied before a response to fertilizer can be expected.

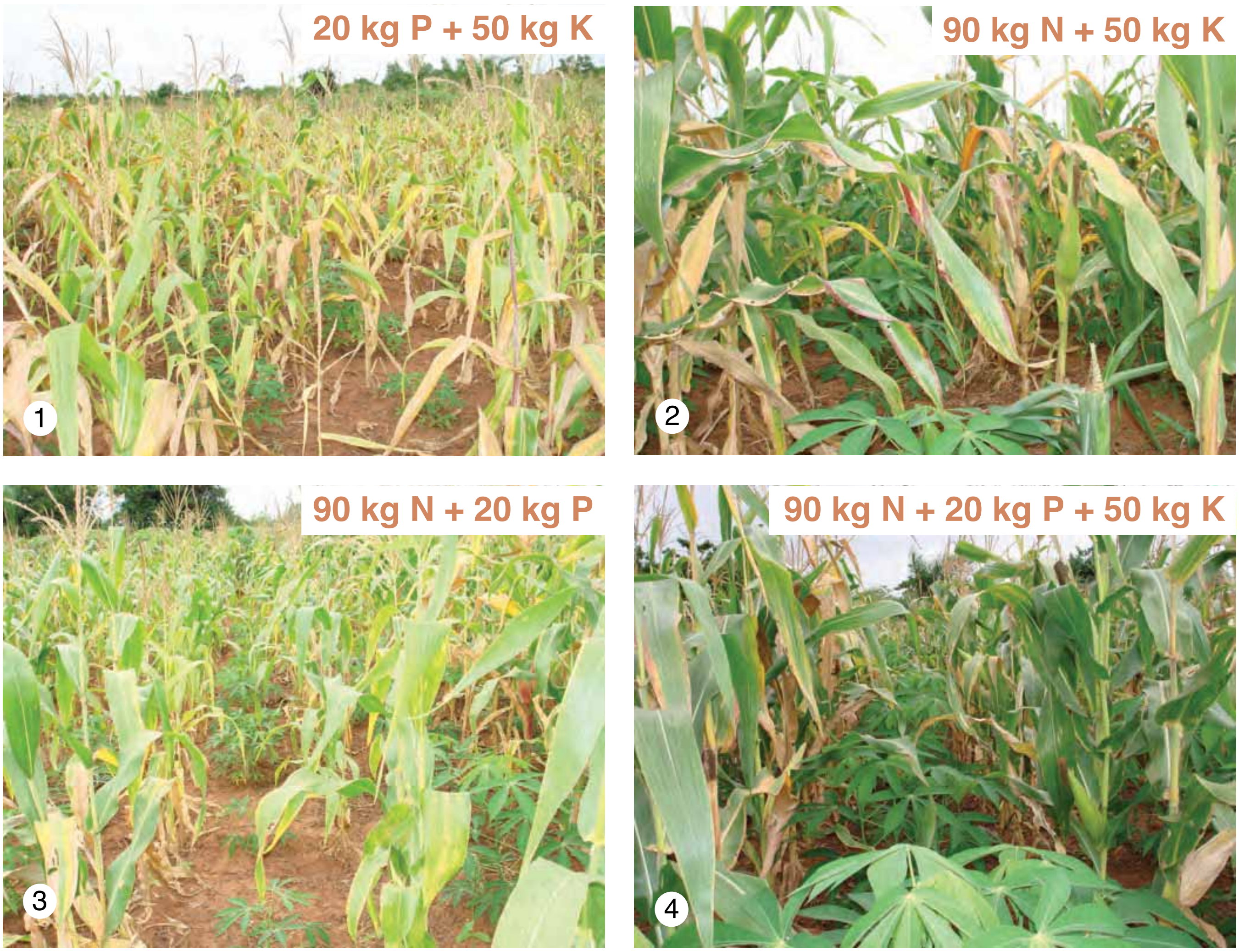


Photo 3.4 A field demonstration to show the effect of different combinations of N, P and K fertilizer on maize intercropped with cassava. With the addition of P and K fertilizer but without N fertilizer (1) plants are small and leaves are pale green-yellow. With the addition of N and K but no P fertilizer (2) plants are larger but P deficiency symptoms are evident. With the addition of N and P but no K fertilizer (3) plants show K deficiency symptoms. When N, P and K fertilizers are applied together, maize and cassava growth is better than the other three treatments suggesting that all three nutrients are required to optimize yield.

4 Soil fertility management practices

4.1 Introduction

In this section we review in detail: (i) the use of organic and mineral fertilizer inputs; (ii) how to calculate fertilizer use efficiency; (iii) how to apply fertilizers efficiently and minimize nutrient losses; (iv) the importance of using improved but adapted germplasm; (v) how to harness the benefit of N_2-fixing legumes; and (vi) the benefits of mycorrhizal fungi. We also provide a review of conservation agriculture (CA) and organic agriculture and the need to adapt technologies to suit the needs of particular farm conditions. Lastly we stress the need for economic analysis to determine whether or not particular ISFM strategies provide economic benefits to the farmer.

4.2 Use of organic inputs

Organic inputs used in soil fertility management commonly consist of livestock manures (farmyard manure), crop residues, woodland litter, household organic refuse, composted plant materials (compost), and any plant biomass harvested from within or outside the farm environment for purposes of improving soil productivity. In urban and peri-urban areas, organic inputs can also be made up of industrial organic waste and sewage sludge.

Organic resources have multiple functions in soil, ranging from their influence on nutrient availability to modification of the soil environment in which plants grow. Organic inputs derived from plant remains provide most of the essential nutrient elements, but usually insufficient quantities. Because of their richness in carbon, organic resources provide an energy source for soil microorganisms which drive the various soil biological processes that enhance nutrient transformation and other quality parameters of soil.

As these organic materials undergo the process of decomposition (or breakdown) in soil, they contribute to the formation of soil organic matter (SOM), which is generally considered to be the backbone of soil fertility. Most of the lasting impacts of organic inputs on soils are related to the functions of SOM. During decomposition, the organic materials interact with soil minerals forming complex substances that influence nutrient availability (e.g. binding of otherwise toxic chemical substances such as aluminium or leading to better release of phosphorus bound to soil mineral surfaces).

4.2.1 Organics as sources of nutrients

The role of organic materials as nutrient sources is underpinned by the biological processes of decomposition, which involve the biochemical breakdown of dead organic tissue into its inorganic constituent forms, primarily through the action of microorganisms. The process by which essential nutrient elements in unavailable organic forms are converted into their inorganic forms that are available for use by growing plants is known as mineralization. It is during decomposition of organic materials in soils that SOM is formed and nutrients are released. SOM can therefore said to be made up of organic materials of diverse origin that are at various stages of decomposition through the action of soil microorganisms.

Soil microorganisms also grow, multiply and die during the process of decomposition and, in turn, contribute to the dynamic changes in SOM formation and mineralization (nutrient release). The amounts of SOM formed as well as quantities of nutrients released depend on the amount and frequency of organic inputs applied to the soil.

Under undisturbed natural vegetation such as permanent forests or grasslands, there is usually an equilibrium between the organic materials added to the soil in the form of plant litter and the SOM status because nutrients are tightly recycled and not removed in crop products. When the soil is used to cultivate crops, however, the rate of SOM formation and nutrient release is less than the demand for nutrients by crops, particularly when farmers aim for commercial yields. Extra effort is therefore required to add more organic materials to the soil, necessitating the use of mineral fertilizer to increase the amount of organic resources available for use in crop production.

Soil organic matter is a significant source of nitrogen (N), phosphorus (P) and sulfur (S) in crop production. The supply of these nutrients from SOM is dependent upon a number of factors including:

- the *quantity* and frequency with which organic inputs are added to the soil;
- the *quality* of the organic resources; and

- the effect of soil type (e.g. texture and mineralogy) and environmental conditions (e.g. moisture and temperature) that provide an environment in which the processes of decomposition and mineralization occur.

While environmental conditions have a significant influence on the rate of activity of the microorganisms that mediate organic matter decomposition, the other key factor is the chemical composition or 'quality' of the organic inputs. Soil microorganisms (microbes) consume carbon (C) as an energy source and N for synthesis of protein and population growth. The ratio of these two chemical elements in a given organic material, termed the C:N ratio, therefore determines the rate of mineralization.

As a general rule, organic inputs with a N content of >2.5% or a C:N ratio <16 release nutrients in the short term, allowing a ready supply of nutrients to growing crops within the same season, and nutrient release can reach a peak within 3 weeks of incorporation into soil. Most high N-accumulating organic materials such as the biomass of N_2-fixing legumes with tissue N contents ≥2% N and composted crop residues fall under this category.

By contrast, organic inputs with an N content of <2.5% or C:N ratio >16 immobilize (literally lock up) nutrients for prolonged periods. This effectively means that when an organic material with a very wide C:N ratio like straw is added to the soil it will immobilize N for a long time because soil microbes out-compete growing plants and lock up the scarce N from the decomposing organic input and the soil into their own tissue production.

This explains why incorporating maize residues in the soil often causes N deficiency unless sufficient amounts of fertilizer are added to supplement the N supply. Most cereal residues (maize, wheat, sorghum and rice), woodland litters and livestock manures fall under this category.

Polyphenols (tannins) and lignin are the other two main chemical components of organic inputs that influence nutrient release from decomposing organic materials when present in large amounts. Net N mineralization of materials that contain large amounts of polyphenols and lignin only takes place very slowly. Some groups of polyphenols bind irreversibly to nitrogen. Lignin is the main component of wood – a complex carbon structure that is difficult for microorganisms to break down.

Using these chemical quality parameters, it is therefore possible to rank organic inputs on a scale according to the ease with which they mineralize and release nutrients for uptake by growing plants. If laboratory analysis is available, a simple decision support diagram can be used to classify residues based on N content and lignin/polyphenol content (Figure 4.1). A simpler method relies on the colour, fibre content and taste of the materials (Figure 4.2).

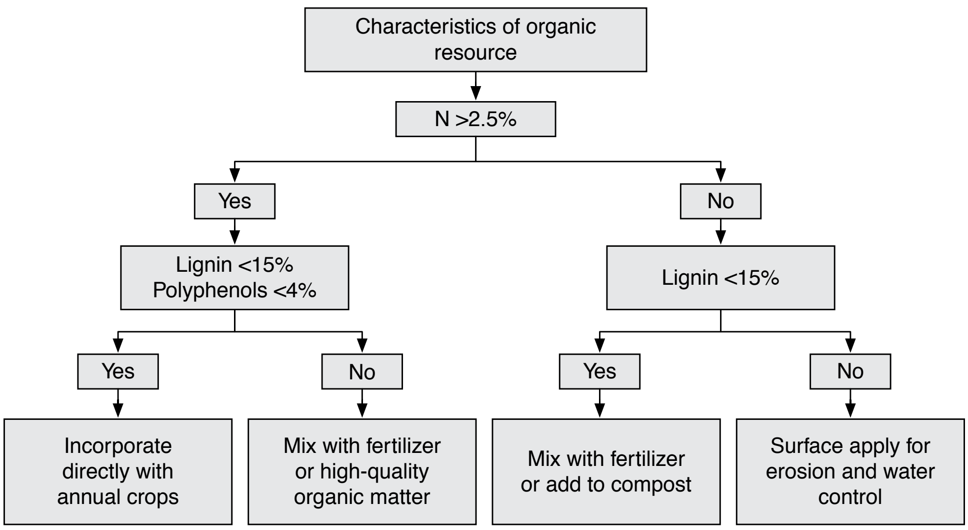


Figure 4.1 A decision tree to assist management of organic resouces in agriculture.

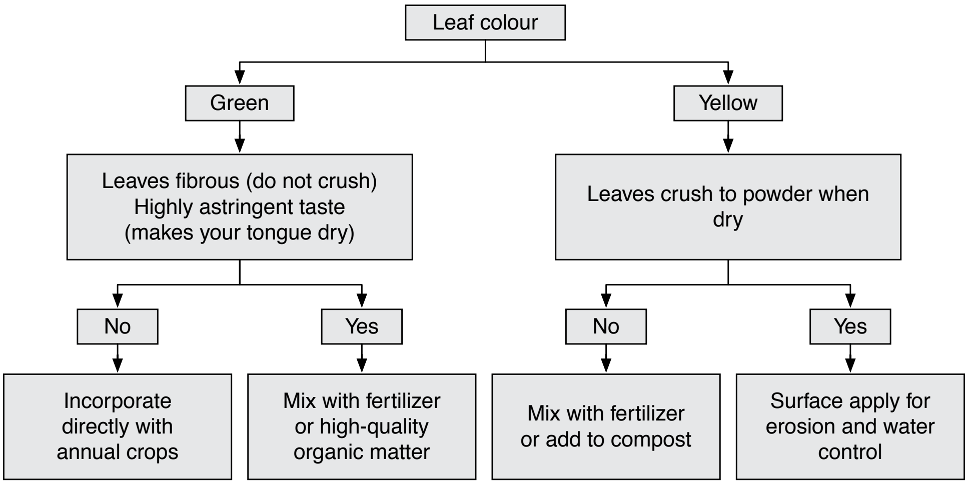


Figure 4.2 A farmer-friendly version of the decision tree in Figure 4.1.

4.2.2 The role of SOM in soil fertility

By directly supplying available forms of C that stimulate soil biological activity and contribute to SOM formation, organic inputs also influence soil chemical and physical properties. The roles of SOM in improving soil productivity include:

- regulation of the rates and amounts of nutrients released for plant uptake in soils;
- improvement of soil water infiltration rate and soil water-holding capacity;
- increasing cation exchange capacity, or the soil's capacity to store nutrients;
- enhancing soil aggregation (SOM particles act as binding agents), improving soil structure, reducing bulk density and promoting good aeration; and
- binding of toxic elements in soils and minimizing their impacts on growing plants.

4.2.3 Advantages and disadvantages of organic inputs as fertilizers

Organic inputs have several *advantages* in soil fertility management. Apart from providing essential plant nutrients, they contribute directly towards the build-up of SOM and its associated benefits. Nutrients are released slowly from organic resources compared with mineral (inorganic) fertilizers, and provide a continuous supply of nutrients over the cropping season. Nutrient losses (e.g. through leaching) are therefore small provided that crops are growing well and provide sufficient demand for the nutrients released. Organic inputs modify the soil environment, directly improving soil biological properties and often enhancing overall soil productivity.

The major *disadvantage* of organic inputs is their relatively low nutrient contents. For example, most organic resources used on farms contain 0.5–2.5% N, or 5–25 g N/kg, compared with >100–460 g N/kg, contained in mineral fertilizer. Organic inputs are therefore required in large quantities if they are to supply significant amounts of nutrients to growing crops. For example, about 2000 kg dry matter of high-quality legume biomass will supply about 50 kg N, enough N for the production of about 1 t of maize grain. The same amount of N can be supplied by about 90 kg or two bags of urea fertilizer.

Such large biomass quantities are, however, not always easy to find in resource-constrained smallholder farming systems. For example, it takes a reasonably fertile soil to grow large biomass of even some of the stress-tolerant legumes. The farmer may be faced with choosing between retaining crop residues in the field to improve soil fertility and removing crop residues to provide fodder for livestock or for sale. He/she may be well aware that removing crop residues deprives the soil of nutrient replenishment but, at the same time, give priority to feeding crop residues to his/her cattle, which provide a means to accumulate valuable assets that can be transferred into cash at a later date.

On-farm handling of organic inputs also requires substantial investments in labour for transport and field application. Green manure biomass can be produced *in situ* (i.e. in the field where they will be used), but this may involve investments in mineral fertilizer on land that could be used instead to grow crops for home consumption or for sale. Such practices are often only possible when returns from the cropping system that will benefit from organic inputs are expected to be very large.

It should be noted that organic inputs can also increase the activity of insect pests and other soil organisms that are harmful to growing crops, attracting extra costs to control diseases and pests.

4.3 Use of mineral fertilizers

Fertilizer is a material that contains at least one of the plant nutrients in chemical form that, when applied to the soil, is soluble in the soil solution phase and 'available' for plant roots. Some fertilizers such as urea, potassium chloride (KCl) and diammonium phosphate (DAP) are completely soluble in water, while others such as rock phosphate and dolomite are partly soluble and release nutrients slowly over several months or years.

The objective of fertilizer use is to deliver nutrients to crop plants. As a guide, fertilizer materials should contain at least 5% of one or more of the essential nutrients in an immediately available form. The nutrient content of proper mineral fertilizers is always stated on the bag label. The P, potassium (K) and magnesium (Mg) content is expressed in the oxide form, i.e. P_2O_5, K_2O and MgO. Secondary and micronutrients are often included in compound fertilizers.

4.3.1 Fertilizer materials

Most essential elements whether macro or micro can be sourced from fertilizer products. Basal or 'starter' fertilizer is applied at planting, usually followed by a second application (referred to as a 'top dressing') of N later in the growing season. Basal fertilizers contain nutrients (e.g. N, P, K and Mg) required for the early stages of plant growth or nutrients that are not easily lost from the soil.

N fertilizers

It should be remembered that all N used by crops is ultimately derived from atmospheric N. While legume plants convert atmospheric N_2 into mineral N by biological fixation, N fertilizer is produced by converting atmospheric N_2 into ammonia (NH_3) using the Haber–Bosch industrial process which uses natural gas as an energy source.

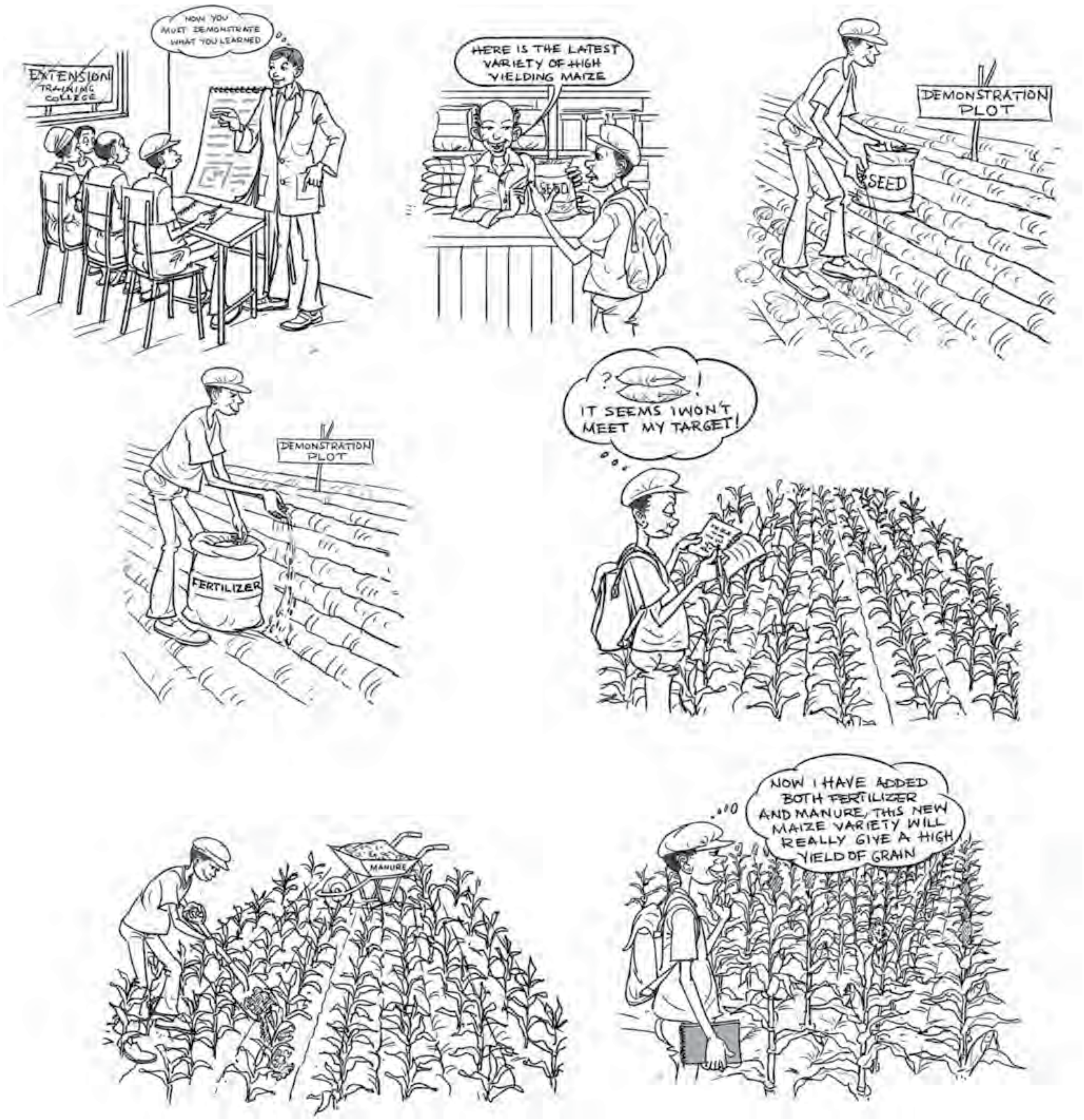
The most common N fertilizer is urea but compound NPKs are often used as a source of N for basal fertilizer application. Other N fertilizers include anhydrous ammonia, calcium ammonium nitrate, ammonium nitrate and ammonium sulfate.

Nitrate (NO_3^-) and ammonium (NH_4^+) are the major N sources released from N fertilizers and available for plant uptake. Nitrate anions are directly available for the plant, but are also easily leached out of the root zone. Ammonium may be taken up directly by the plant or first oxidized to nitrite in a process called nitrification and then transformed into nitrate by nitrifying microorganisms.

Nitrification results in the release of hydrogen ions (H^+), which leads to soil acidification. If all nitrate ions produced through nitrification are absorbed by plant roots, excretion of OH^- by the plant neutralizes the hydrogen ions. In general, however, only a fraction of total nitrate produced is absorbed by the plant roots.

P fertilizers

All fertilizer phosphorus is derived from mined phosphate ore rocks of either sedimentary or igneous origin. Phosphate rock (PR) of sedimentary origin is generally more reactive with the soil than igneous PR and is therefore more suitable for direct application, provided it is ground into small particles so that there is a large surface area on



the rock phosphate particles that can react with the soil and release P for plant uptake. Phosphate rocks are highly variable in both P content and P availability.

There are several drawbacks to the use of PR for direct application:

- PR has relatively low P content in comparison with most manufactured fertilizers, which increases shipping costs and labour for application.
- The very fine powder that must be produced to ensure sufficient solubility may be difficult to handle and apply (but some PR, e.g. Minjingu, is available in a pelleted form).
- The soil must be sufficiently acid (generally pH <5.5) to provide a reaction with the PR and release P for plant uptake.

- The rate of release of P from PR may be too slow to satisfy crop demand. PR is a good P source for tree crops where a slow and continuous release of P is required over the long term. PR has also been used to recapitalize soil P reserves in degraded soils. In most cropping systems, however, soluble P fertilizers such as triple superphosphate (TSP) and DAP are more suitable for the production of annual crops.

Total P_2O_5 content in PR is of limited use as a measure of the amount of P that will be provided for plant uptake. Instead, it is more useful to measure the amount of P soluble in citric and formic acid as well as fineness, which also affects the rate of P release from the material (Table 7.39).

In general, PR derived from sedimentary rocks is more soluble and supplies P better than PR derived from igneous sources. While PR is sometimes used for direct application it is more commonly used as a raw material for the manufacture of soluble P fertilizers. In the manufacturing process, PR is reacted with sulfuric or phosphoric acid to produce commercial P fertilizer products that contain a large amount of plant-available P. PR generally contains about 32% P_2O_5, compared with manufactured P fertilizers such as TSP, which contains 46% P_2O_5, and single superphosphate (SSP), which contains 20% P_2O_5. While PR is sparingly soluble, manufactured P fertilizers are fully soluble in the soil.

K fertilizers

All fertilizer potassium is manufactured from very large deposits of water-soluble K minerals that have accumulated as a result of the evaporation of shallow seas or natural lakes over geological time. The most widely used K salts in agriculture to produce K fertilizers are double salts that also contain significant quantities of Mg and S. The most commonly available K fertilizers are potassium chloride (KCl) containing 60% K_2O and potassium sulfate (K_2SO_4), which contains 50% K_2O.

Potassium sulfate is usually more costly than potassium chloride but is more suitable for use on high-value crops where sugar content is important (pineapples, sugarcane, fruit crops) and in tobbaco where chlorine content in the product must be minimized.

Multinutrient fertilizers

Multinutrient fertilizers can be divided into three types:

- **Complex multinutrient fertilizers** are designed for use in horticulture where high-grade fertilizers are required. They are generally too costly for use in small-scale farming in SSA.
- **Compound fertilizers** are manufactured by mixing compatible straight fertilizers to produce a slurry from which a granulated product is prepared. Compound fertilizers are less costly to produce than complex multinutrient fertilizers.
- **Bulk blend fertilizers** are prepared by physically mixing different fertilizers to achieve a specific nutrient composition. Bulk blend fertilizers are less costly to produce than compound fertilizers.

Compound and bulk blend ferilizers are often produced with nutrient content suited to particular crops such as 8-14-7 (maize), 5-18-10 (cotton) and 5-7-15 (tobacco) (Table 4.1). Other bulk blends and compounds (e.g. 15-15-15, 12-12-17+2, 15-15-6+4) can be used for a wide range of crops.

It is important to compare the cost of different fertilizer sources. Multinutrient fertilizers are usually more costly than straight fertilizers in terms of dollars per kilogram of nutrient because of the manufacturing costs involved. Bulk blends are usually only slightly more costly than straight fertilizers because the blending process is not very expensive. Bulk blends tend to settle into their constituents during shipping and may require mixing before application.

Some manufacturers retail fertilizers in small bags (25 kg/bag or less) that are more convenient for small-scale farmers than the standard bag size of 50 kg.

Worked example

It is always worthwhile comparing compound and straight fertilizers to find out which source is the least costly, as illustrated in the following example.

A farmer wants to compare the cost of applying nutrients in the form of a compound (15-10-12) with straight fertilizers (urea, TSP and KCl). The nutrient content and cost of available fertilizers is shown in Table 4.1.

Table 4.1 Nutrient content and cost of fertilizers available on the market.

Fertilizer	Nutrient content (%)			Price ($/50 kg bag)
	N	P_2O_5	K_2O	
Compound 15-15-15	15	10	12	32
Urea (46% N)	46	–	–	17
TSP (46% P_2O_5)	–	46	–	22
KCl (60% K_2O)	–	–	60	30

First we calculate how much N, P_2O_5 and K_2O are contained in one 50 kg bag of compound 15-10-12:

- One 50 kg bag of the compound 15-10-12 contains 7.5 kg N, 5 kg P_2O_5 and 6 kg K_2O.

To supply the same amount of nutrients as straight fertilizers we need to apply:

Urea (nitrogen)

- 50 kg compound (15-10-12) x 15% N = 7.5 kg N
- 7.5 kg N ÷ 46% N in urea = 16.3 kg urea

TSP (phosphorus)

- 50 kg compound (15-10-12) x 10% P_2O_5 = 5 kg P_2O_5
- 5 kg P_2O_5 ÷ 46% P_2O_5 in TSP = 10.9 kg TSP

KCl (potassium)

- 50 kg compound (15-10-12) x 12% K_2O = 6 kg K_2O
- 6 kg K_2O ÷ 60% K_2O in KCl = 10 kg KCl

Now we can calculate the costs:

- One 50 kg bag of compound 15-10-12 costs $32.
- One 50 kg bag urea costs $32 so 1 kg costs 32 ÷ 50 = $0.64 and 16.3 kg costs 16.3 kg x $0.64 = $10.43.
- One 50 kg bag TSP costs $22 so 1 kg costs 22 ÷ 50 = $0.44 and 10.9 kg costs 10.9 kg x $0.44 = $4.78.
- One 50 kg bag KCl costs $30 so 1 kg costs 30 ÷ 50 = $0.60 and 10.0 kg costs 10.0 kg x $0.60 = $6.00.

Total cost of straight fertilizers = $10.43 + $4.78 + $6.00 = $21.21.

The cost of nutrients supplied as the equivalent of one bag of compound fertilizer as straight fertilizers is $21.21, a saving of $10.79. It is important also to note that the total amount of straight fertilizers required in this example is 37.2 kg, a smaller quantity than the 50 kg of compound fertilizer.

In this example the straight fertilizers are less costly. The farmer may yet choose to apply the compound fertilizer because he/she considers the advantage of applying all nutrients in one fertilizer material more than offsets the additional cost of $10.79.

Bulk blends and other fertilizers

Dry NPK bulk blend fertilizers can be prepared by physically mixing granular straight fertilizers in the proportions required to deliver the right amount of each nutrient to the crop. Sulfur and micronutrients are sometimes added to NPK blends if they are needed.

Most NPK blends are prepared using P from DAP. Granular TSP is used to manufacture fertilizers containing P and K but cannot be used to produce NPK bulk blend fertilizers because it is incompatible with urea, the fertilizer N source most commonly used in blends. Blends are prepared according to the particular nutrient requirements of crops. For example, cassava and plantain require blends containing a large amount of K.

Farmers can also make fertilizer mixtures provided the materials are compatible (Table 7.34).

4.3.2 Soil amendments

Lime

Liming materials are used to increase the pH in acid soils where crops are intolerant of high aluminium (Al) saturation, which often (but not always) accompanies low soil pH. By correcting soil pH and supplying calcium (Ca), lime improves the soil environment for plant growth. In some very acid soils (pH <5.5), Al and manganese (Mn) toxicity is prevented and P and molybdenum (Mo) availability is increased following an application of lime. Other microbiological processes such as nitrification and N_2-fixation are also improved and liming may contribute to improved physical soil properties because of increased microbial activity. Acidity is often associated with highly leached soils which are deficient in Ca and Mg so that lime plays an important role in supplying these nutrients.

The most commonly used liming material is limestone or calcium carbonate ($CaCO_3$), and all other liming materials are evaluated in terms of their relative effectiveness when compared with calcium carbonate (expressed in calcium carbonate equivalent, CCE, where $CaCO_3$ has a CCE of 100).

Limestone deposits are found all over the world and are usually mined by open-pit methods using explosives. Broken rock pieces are crushed to sizes of <2.5 cm and further ground or pulverized. The quality of commercial limestone is generally 90–98% CCE. Other liming materials include calcium oxide (CaO) with a CCE of about 180%, calcium hydroxide ($Ca(OH)_2$) with a CCE of about 135% and dolomite ($CaMg(CO_3)_2$) with a CCE of about 110%.

A distinction is made between dolomitic limestone, which contains both $MgCO_3$ and $CaCO_3$, and calcitic limestone which contains only small amounts of $MgCO_3$. On some soils calcitic limestone may induce Mg deficiency if applied in large quantities.

The liming requirement of a soil depends on soil acidity level and the level of exchangeable Al^{3+} that a particular crop can tolerate. The lime requirement is often calculated as the amount needed to reduce Al saturation to 15%. Sandy soils are weakly buffered so that small amounts of lime are needed to provide Ca and correct acidity. By contrast, larger amounts of lime are required to reduce Al saturation in strongly acid clay soils due to their larger buffering capacity. Liming requirements are calculated using empirical formulas that are a function of Al saturation on the soil's exchange complex.

Gypsum

Gypsum ($CaSO_4.2H_2O$) is a mineral that occurs as a natural deposit in semi-arid and arid regions and is sparingly soluble in water. Gypsum is used to rehabilitate sodic soils that have, by definition, a very high percentage of sodium on the cation exchange complex (i.e. >15%). Such sodic soils often have a degraded soil structure because of the collapse of clay minerals. Gypsum is usually incorporated during land preparation to a depth of 0–15 cm. Gypsum reacts with sodium (Na) salts (e.g. sodium carbonate) and replaces exchangeable Na on the exchange complex, which is then leached out as sodium sulfate.

Gypsum is also used to correct Ca deficiency in crops, such as groundnut, that have a large Ca demand during podding.

4.4 Fertilizer use efficiency

Most soils cannot supply all essential nutrients in sufficient amounts to support good growth of crops, and the application of fertilizer is one of the most effective means to increase nutrient uptake in crop plants and improve yields.

Nutrients applied to the soil are either:

- taken up by the crop;
- retained in the soil as soil nutrient stocks; or
- lost from the soil through various processes.

Fertilizers produce direct benefits by increasing crop yields and indirect benefits by increasing the amount of crop residues available to replenish soil organic matter or for use as livestock fodder. When more livestock fodder is available, livestock produce greater amounts of manure containing nutrients that can be recycled to the field. In this way nutrients contained in mineral fertilizers become part of the nutrient cycle between the soil, crops and livestock.

To use fertilizer in a sustainable manner, management practices must aim at maximizing the amount of nutrients that are taken up by the crop and minimizing the amount of nutrients that are lost from the soil. The proportion of nutrients that are taken up and used to produce grain is referred to as agronomic efficiency (AE). We measure efficiency of fertilizer use by answering two questions that the farmer might ask:

- *For each kilogram of nutrient I apply how much is taken up by the crop?* Scientists refer to this as fertilizer nutrient ‘recovery fraction’.
- *How much additional yield will I obtain for each additional kilogram of nutrient taken up by the crop?* Scientists refer to this as ‘internal use efficiency’.

We use these two terms because we need to understand first whether the nutrients applied have been taken up by the crop plants and, if the nutrients have been taken up, whether they resulted in increased crop yields.

Fertilizer use efficiency can be estimated from the results of fertilizer omission plots where the uptake of each nutrient can be compared in fertilized and unfertilized plots. For example, to estimate N fertilizer use efficiency we compare N uptake in a plot receiving N, P and K fertilizer with a plot where only P and K fertilizer is applied. In both plots P and K are applied to eliminate these nutrients as constraints to N uptake. It is of course only possible to use single-nutrient fertilizers for these trials.

To calculate agronomic efficiency we must first estimate the recovery fraction:

The **recovery fraction (RF)** of applied nutrients, e.g. for nutrient X, is defined as:

$$RF - X = \frac{Xupt_F - Xupt_C}{X_{appl}}$$

where:

- RF-X is the recovery fraction of applied nutrient X (kg X uptake/kg X applied).
- $Xupt_F$ is plant X uptake at harvest when nutrient X is applied (kg X uptake/ha).
- $Xupt_C$ is plant X uptake at harvest without nutrient X (kg X uptake/ha).
- X_{appl} is the rate of nutrient X applied (kg X/ha).

The **internal use efficiency** of nutrients, e.g. for nutrient X, is defined as:

$$IE - X = \frac{Y_F - Y_C}{Xupt_F - Xupt_C}$$

where:

- IE-X is the internal efficiency of nutrient X (kg crop product/kg X uptake).
- Y_F refers to yield (kg/ha) obtained with nutrient X.
- Y_C refers to yield (kg/ha) obtained without nutrient X.
- $Xupt_F$ is plant X uptake at harvest with nutrient X (kg X uptake/ha).
- $Xupt_C$ is plant X uptake at harvest without nutrient X (kg X uptake/ha).

We can then combine these two terms to calculate the **agronomic efficiency** (AE) of a particular nutrient (AEN), expressed in (kg crop product/kg X applied) is defined as:

$$AE - X = \frac{Y_F - Y_C}{X_{appl}}$$

where:

- AE-X is the agronomic efficiency of nutrient X.
- Y_F refers to yield (kg/ha) obtained with nutrient X.
- Y_C refers to yield (kg/ha) obtained without nutrient X.
- X_{appl} is the level of nutrient applied (kg X/ha).

Agronomic efficiency can also be obtained by multiplying the recovery fraction by internal use efficiency:

$$AE\text{-}X = RF\text{-}X \times IE\text{-}X$$

Fertilizer use efficiency by most crops and farming systems is still very poor. For example, it is has been estimated that two-thirds of the nitrogen fertilizer applied in irrigated rice systems is not taken up by rice plants to produce biomass and fulfil physiological functions but is instead lost due to leaching, volatilization and denitrification.

Improving agronomic efficiency provides both direct and indirect economic benefits:

- Larger yield increases can be achieved for a given quantity of fertilizer applied.
- Less fertilizer is required to achieve a particular yield target.

Worked example

Fertilizer use efficiency depends to large extent on soil fertility conditions. When two farmers with fields varying in soil fertility apply 50 kg N/ha fertilizer with similar management, the crop yields increase and the fertilizer use efficiency may vary as follows.

Farmer 1

Field history: Degraded field, cultivated for many years without addition of fertilizer or manure.

Yield without N application: 400 kg/ha

Yield with 50 kg N/ha: 900 kg/ha

Agronomic N use efficiency = (900 – 400) ÷ 50

= 10 kg grain/kg N

Farmer 2

Field history: Fertile but N-deficient field that received moderate rates of manure in the past.

Yield without N application: 2000 kg/ha

Yield with 50 kg N applied/ha: 4500 kg/ha

Agronomic N use efficiency = (4500 – 2000) ÷ 50

= 50 kg grain/kg N

Interpretation

Clearly Farmer 2 is achieving much better returns for investments in mineral fertilizer compared with Farmer 1. It is important to realize that the agronomic efficiency (AE) of a nutrient like N is influenced by many factors other than fertilizer N application. To increase the efficiency of mineral fertilizers it is essential to adopt an integrated crop management approach to manage all growth-limiting or growth-reducing factors as well as possible. In both these examples, AE of N might be increased by applying other nutrients such as P and K fertilizer.

With good crop management, the efficiency of mineral fertilizers can be further improved by using the right techniques for applying fertilizer. These techniques are often called the ‘4Rs’ of fertilizer use.

4.5 The '4Rs' for effective fertilizer use

The four best management practices, commonly referred to as the 4Rs or four 'rights' of fertilizer management are to apply the right source of nutrient at the right rate, at the right time and in the right place to meet crop demand. These 4Rs help to improve the recovery fraction of fertilizer and therefore contribute to improved agronomic efficiency.

4.5.1 Right fertilizer product

The right fertilizer product means matching the fertilizer source and product to the crop's needs and the properties of the soil.

- Fertilizer can be applied as straight fertilizers that provide one nutrient or compound fertilizers and bulk blends that provide more than one nutrient. As mentioned above, compounds provide several nutrients in one product and therefore offer some convenience to the farmer over the use of straight fertilizers. They are often more costly, however, and should be used if they are more cost effective than straight fertilizers. In the end the farmer's choice will be affected by the local availability of fertilizer materials.
- It is important to be aware of interactions between nutrients. For example, the application of P and K fertilizer may be required in order to achieve a full response to N fertilizer. So-called 'balanced fertilization' therefore is an important aspect of increasing fertilizer use efficiency.
- The choice of fertilizer will depend on the particular crop, current and past use of manure, as well as soil properties and climate conditions. For example, where soils have a low buffering capacity (e.g. sandy soils), it would be unwise to use ammonium sulfate as a source of N due to its soil-acidifying potential, while in areas with very heavy rainfall during the cropping season it is better to avoid nitrate-based fertilizers because they are more prone to leaching than ammonium-based fertilizers such as urea.
- Several methods are used to identify which nutrients are deficient in the soil, and these include soil analysis, nutrient omission trials and nutrient deficiency symptoms observed on crops.
- Even though some nutrients may not be deficient over the short term, it may be worthwhile to apply small amounts to avoid depleting soil nutrient stocks that lead to nutrient deficiencies over the long term. Some soils have large reserves of particular nutrients that can be exploited for many years without any negative effects. Soil analysis and omission plots are required to determine whether there are sufficient stocks of particular nutrients to sustain crop production without fertilizer application.
- Not all fertilizer products available on the market are of good quality. If a farmer buys and uses adulterated or poor-quality fertilizer, it will not increase yields as expected as it does not contain the correct amounts of the required nutrients. For fully soluble fertilizers like urea, ammonium sulfate, ammonium nitrate, KCl, TSP and DAP, farmers can find out if the fertilizer has been adulterated with sand or brick dust by adding 100 g fertilizer to 1 l of water. Unadulterated fertilizers will dissolve in water, cause a decrease in water temperature and leave only a very small undissolved residue.

4.5.2 Right fertilizer rate

General guidelines

The right fertilizer rate means matching the amount of fertilizer applied to the crop's needs.

- Fertilizer rates are site- and crop-system specific and are estimated after considering:
  - the nutrient requirements of the crop;
  - the soil's capacity to supply nutrients (measured by soil analysis and omission plots);

- the amount of nutrients applied in crop residues and farmyard manure;
- the amount of nutrients applied to previous crops;
- the target yield;
- the attainable yield under local climatic conditions; and
- the cost of fertilizers and the value of crop products.

- Applying too much fertilizer leads to waste of nutrients not taken up by the crop and possible contamination of the environment. On the other hand, applying too little fertilizer results in less yield and crop quality and less crop residues to protect and build the soil or for use as animal fodder.
- In many areas in SSA published fertilizer rates for a particular locality are out of date and are geared towards maximizing yield rather than the farmer's economic returns. It is very important to assess the farmer's goals and attitude to risk before recommending fertilizer application rates.

Fertilizer responses

Fertilizer responses can be classified as follows:

- poor responses on fertile soils with large nutrient reserves (often the fields lying close by the farmer's house where fertilizers, animal manures and crop residues have been applied regularly in the past);
- large responses to fertilizer on nutrient-deficient but responsive soils (often the fields more distant from the farmer's house where fertilizers, manures and crop residues are not applied); and
- very poor responses to fertilizer application on degraded soils where fertilizers must be applied in combination with large amounts of organic inputs (crop residues, animal manures) in order to obtain satisfactory responses to mineral fertilizer.

Approaches to address these include:

- Application of small amounts of fertilizer and/or manure on fertile soils can sustain soil fertility.
- Resource poor farmers can invest limited cash most effectively by prioritizing fertilizer use in their most responsive fields and using moderate amounts that achieve a large return in yield per kilogram of fertilizer applied (i.e. high AE).
- Application of organic resources may be required to rehabilitate non-responsive soils before a response to mineral fertilizer is obtained.
- In some non-responsive soils the application of organic resources may not result in a response to mineral fertilizers and other techniques may be required (e.g. tillage, application of micronutrients).

Practical steps to improve fertilizer application rates

- Soil testing, omission plots, crop nutrient budgets, tissue testing, plant analysis, applicator calibration, crop scouting, record keeping and nutrient management planning are tools that will help determine the right rate of fertilizer to apply.
- Here are some practical steps to help farmers improve the application rates of fertilizers:
  - Gather together any information available from fertilizer trials, particularly if they were carried out in farmers' fields in the locality in which you are working. Which nutrients improved yield? Did fertilizer increase farm profits as well as yields? How much of each nutrient was required to achieve economic increases in yield?
  - Such information may not be available but, even if it is, supplement this information from trials by finding out how much and what kind of fertilizers farmers are presently using and what response in terms of yield increases has been obtained. Draw up a table listing each farmer, the amount of nutrients applied, the field history (i.e. whether fertilizers have been applied consistently in past cropping seasons) and the yield achieved.

- All field workers should spend as much time as possible walking the fields, looking at crops for signs of nutrient deficiency symptoms, crop stunting and retarded development (often due to P deficiency).
- Identify farmers that are currently achieving high yields and profits. Find out how much fertilizer they are using and what yields they are achieving. Make an inventory of all the soil fertility practices they are using that may be applicable to other farmers.
- If possible, carry out soil sampling and analysis to assess soil fertility, particularly the amount of available phosphorus and exchangeable potassium and magnesium.
- Work with farmers to test fertilizer recommendations, starting with low application rates.
- Record the results of your work in a field book to build up a knowledge base of reliable information on fertilizer use and crop responses for your locality. After a few years it may be possible to make an assessment of the risk of crop failure so that farmers can be informed about the economic risks of applying fertilizer.

Techniques for accurate application

A calibrated measure should always be used to apply fertilizer! To apply fertilizer uniformly at the right rate in a large field, soft-drink-bottle tops can be used to measure the amount of fertilizer applied to each plant. For example, a full, level soda-bottle top contains about 6 g of fertilizer. In a maize field with a plant population of 40,000 plants, an application of one soda-bottle top of urea is equivalent to 24 kg N/ha.

4.5.3 Right time for fertilizer application

The right time for fertilizer application means making nutrients available when the crop needs them.

- Nutrients are used most efficiently when their availability is synchronized with crop demand. Basal fertilizer application is done at or just after planting to supply N, P, K and other nutrients required for early crop growth.
- Fertilizer N is highly mobile and easily lost from the soil due to leaching so some fertilizer N should be applied as a 'top dressing' at key stages during crop development, usually when the crop is growing fastest.
- Top-dressed fertilizer N can be applied as several split applications to improve fertilizer use efficiency. Top-dressing rates can be adjusted according to how well the crop is developing and the expected price of crop products.
- Top dressings produce good agronomic results if the crop is developing well under favourable climatic conditions and good economic results if high crop prices are expected. If the crop has developed poorly because of poor rainfall and the price of crop outputs is expected to be low, top dressings can be cancelled and the fertilizer set aside for the next planting season.
- Application timing (pre-plant or split applications), controlled release technologies, stabilizers, inhibitors and product choice are examples of practices that influence the timing of nutrient availability.
- Leaf colour charts or chlorophyll meters are available on the market to guide the application of N, based on crop demand.
- Slow-release N fertilizers and deep placement of fertilizer N improve the match between nutrient release and crop demand (sometimes referred to as synchrony).
- Look-up tables are also available to guide decision making on the timing of fertilizer application.

4.5.4 Right placement of basal fertilizer

The right placement of fertilizer means applying fertilizer where the crop can access the nutrients contained in the fertilizer. The choice of application method by the farmer will depend on the labour required.

- Application methods should be selected based on the particular crop or cropping system and soil properties. It is usually best to incorporate basal fertilizer in the soil at or before planting to achieve efficient fertilizer use.

- There are four main fertilizer placement methods:
  - **Broadcasting.** Fertilizers are applied uniformly to the soil surface. This is done either before sowing or in the standing crop. The method is easy to implement and has low labour requirements. N fertilizer top dressings are usually broadcast in irrigated rice fields.
  - **Banding.** Fertilizers are placed in a band at a depth of 5–8 cm below the soil surface and covered by the soil. Seeds are planted above the covered fertilizer. Banding is the most common method of placement for basal fertilizer applications.
  - **Spot application.** Fertilizers are applied in small amounts either at planting in each plant hill together with the seed or close to each plant station during the crop growing season. Spot application is preferred where plants are widely spaced and where soil and climate conditions increase the risk of nutrient losses due to leaching. Spot application is becoming popular among farmers because it is more cost effective than broadcasting.
  - **Deep placement.** Slow-release N fertilizers are placed in the soil in flooded fields.
- Conservation tillage, buffer strips of non-crop vegetation around crop plants and irrigation management are measures that will help keep fertilizer nutrients where they were placed and accessible to growing crops.

4.5.5 A fifth 'right' for fertilizer use in SSA – targeting the most remunerative options

Because farmers in SSA often have limited cash resources and often buy small amounts of fertilizer, it is important to identify the part of the farm system where fertilizer inputs will deliver the greatest return. When used with such care, fertilizer becomes the key to unlocking the potential of the farm. As already discussed, soil fertility varies among the farmer's different fields so it is important to know which fields will deliver the greatest return on fertilizer use.

A second point is to consider the cropping system rather than a single crop when planning fertilizer use. For example, in a maize–grain legume rotation, fertilizers (particularly N) applied to the maize crop will provide a residual benefit in terms of nutrient supply to the following legume crop, which may therefore not need to be fertilized.

Fertilizers should be provided to the main crop in intercropped systems. In a field of intercropped maize and beans, for example, N fertilizer should be applied to the maize crop because the beans are able to provide much of their N requirements by biological N_2-fixation.

The 'fifth R', then, is to consider the 'opportunity cost' of fertilizer and make sure that scarce fertilizer resources are delivered to the part of the cropping system that delivers the maximum economic benefit to the farmer.

4.6 Fertilizer use and the environment

Intensification of crop production using ISFM provides the means to increase the productivity of existing cultivated land and therefore helps to reduce the requirement to expand the area under cultivation to meet current and future needs for food, fibre and fuel. Crop intensification therefore may contribute indirectly to conservation efforts by sparing wilderness land from cultivation.

Care must be taken, however, to avoid the negative effects that accompany excessive fertilizer use. In some cases, excessive mineral fertilizer use in industrialized countries has resulted in leaching of N and P into water bodies, causing water contamination and eutrophication. Such negative effects can be avoided by applying fertilizer best management practices to use fertilizers efficiently. Over-use of mineral fertilizers is not of major concern in SSA. Cases where eutrophication occur in Africa are usually associated with effluent from cities or intensive farming practices such as peri-urban agriculture and horticultural enterprises. On the contrary, the most significant environmental issue in SSA is related to depletion of soil fertility and soil degradation, due to insufficient use of mineral fertilizer and organic inputs.

Proper use of mineral fertilizer acts as a catalyst to increase the overall productivity of soils in SSA. They contribute to increased overall biomass production, part of which provides the crop products needed to sustain human life. But by increasing the yield of biomass, greater amounts of crop residues and other organic by-products accrue that provide the materials for soil organic matter replenishment. In addition, more fodder is available for livestock.

4.6.1 Fertilizer use and sustainability

Improving fertilizer use efficiency is key to sustainability. Manufactured fertilizers are non-renewable resources since N fertilizers are manufactured using natural gas as an energy source to transform atmospheric N_2 into ammonia, the raw material for N fertilizer manufacture. About 3–5% of world natural gas use or 1–2% of the world's energy supply is used to manufacture N fertilizers.

Reserves of raw materials for P and K fertilizer manufacture are finite. Based on the presently identified supply base, reserves of potash are sufficient for at least another 250 years while the reserves of phosphate are sufficient for 300–400 years.

4.7 Minimizing losses of added nutrients

An important objective in fertilizer management is to implement management practices that minimize the loss of nutrients added to the farming system. With good management practices, a significant proportion of nutrients added to the farming system in the form of mineral fertilizers or crop residues and manure can be recycled many times through crops and livestock.

Some nutrients taken up by the crop are exported in crop products (grain, tubers) that are exported from the farm but a large part of nutrients taken up by crop plants can be recycled back to the soil in the form of crop residues. Alternatively, crop residues may be used as fodder for livestock and the manure they produce can be recycled to the field. With proper management, nutrients applied to the field build up the nutrient stocks or capital in the farm and add value to the land.

Nutrients added as mineral fertilizer, recycled in crop residues and manure as well as soil nutrient stocks may be lost from the farming system or the farm plot through water or wind erosion, leaching or gaseous losses.

- Nitrogen is the most susceptible to losses because it is very mobile and can be lost due to leaching as well as volatilization. There are three main forms of N 'capital' in the soil:
  - mineral N (ammonium NH_4^+ and nitrate NO_3^-);
  - N in soil organic matter; and
  - N in a more stable form of soil organic matter.

NH_4-N can be held as an exchangeable cation or trapped in the layers within some 2:1 clay minerals, such as montmorillonite, vermiculite and illite. Under aerobic conditions (i.e. well-drained soils) nitrifying bacteria quickly transform NH_4-N into NO_3-N (nitrification). Nitrate is highly mobile and easily lost by leaching or by denitrification (NO_3^- is transformed into the gases NO, N_2O and N_2). Substantial losses of NH_4-N can also occur through volatilization (gaseous losses as NH_3), especially in alkaline soils and where urea is applied to the soil surface.

4.7.1 Water and wind erosion

Water and wind erosion are major factors contributing to the loss of nutrients. Recent studies indicate that annual erosion losses in low-input production systems in SSA are about 10 kg N/ha, 2 kg P/ha and 6 kg K/ha. Losses may be greater in high-input systems, or where rainfall is very high. Water barriers, such as grass strips and stone rows, are effective options to reduce erosion and to keep applied fertilizer and manure in place.

Erosion and runoff can also be reduced by covering the soil with a mulch layer of living or dead biomass. Soil mulch reduces water speed, avoids crust formation and improves soil porosity and infiltration rates. Even a relatively thin layer of mulch provides a significant increase in water infiltration. Indeed, studies have shown that the application of 2 t/ha of straw led to a 60% reduction in runoff and a 90% reduction in erosion. With 6 t/ha of straw mulch, runoff was reduced by 90% and erosion levels were reduced to zero. Leaving straw in the field leads also to significant reduction in soil losses due to wind erosion. In Niger, 1.4 t/ha millet straw cover reduced wind erosion losses by 63%. The problem faced by most farmers is that their priority is to use organic materials for livestock feed.

Soil preparation methods may also be efficient in increasing infiltration and reducing runoff. The so-called 'Zaï' technique is an effective technique to deal with surface crusting: small pits are dug in the soil and small amounts of mineral and/or organic fertilizers are added. Improving SOM content will generally reduce the susceptibility of the soil to form surface crusts and improves soil structure and water holding capacity.

4.7.2 Leaching

Leaching of nutrients occurs if water carrying nutrients percolates beyond the reach of crop roots in the soil profile and the nutrients are, therefore, lost to the crop. Leaching is a particular problem in areas with high rainfall intensity (>30 mm/day) and coarse-textured sandy soils (>35% sand). Leaching concerns mainly mineral N (principally nitrate, NO_3^-) and exchangeable bases (K and Mg) which are often leached together with NO_3^-. Phosphorus is generally not susceptible to leaching except in very coarse-textured sandy soils.

Some studies suggest that 50–60% of K fertilizer applied in banana plantations in Côte d'Ivoire are lost through leaching. Reducing losses due to deep drainage is difficult, but two approaches can be considered:

- Promoting root development by applying nutrients and improving soil structure. This will allow the crop to better profit from water that has infiltrated into the soil below the present depth of root penetration, and therefore reduce the loss of nutrients.
- Association of annual crops and trees – trees can 'pump' water and nutrients from depths below the rooting depth of annual crops, leading to better overall water and nutrient use.

4.7.3 Gaseous losses through denitrification and volatilization

Under anaerobic conditions (e.g. poorly drained field or paddy rice field), nitrate is reduced to N_2O and N_2 (denitrification). Denitrification also occurs in aerobic soils because of the presence of anaerobic microsites that are created following the application of decomposable organic resources. The best way to reduce denitrification in upland fields is to improve soil drainage and maintain a good soil structure to avoid anaerobic growing conditions.

Nitrogen can also be lost by volatilization as NH_3-N losses through volatilization are important in alkaline soils (high soil pH). As much as 60% of N applied as urea on paddy (i.e. flooded rice fields) may be lost due to volatilization. Losses can be reduced by deep placement of N fertilizers, by manual incorporation.

Nitrogen is lost by NH_3 volatilization during the storage and handling of manure. Losses can be reduced by using anaerobic storage pits with or without the addition of crop residues.

4.7.4 Crop residue management

Farmers use crop residues in a number of ways. They may be:

- returned to the field to provide mulch and recycle nutrients;
- used as animal feed (and livestock manure returned to the field);
- used as a fuel source; or
- used as construction materials (e.g. wall construction and roofing material).

The choice the farmer makes will be based on his/her particular circumstances. The only option for conserving nutrient stocks is to retain or incorporate crop residues in the field or to use them as livestock fodder and recycle animal manure or to make compost for use in the cropping system.

Table 4.2 N, P and K concentrations in straw of major cereals in sub-Saharan Africa.

Nutrient	Dryweight (g/kg)[a]					
	Millet	Sorghum	Maize	Rice	Soybean	Groundnut
Nitrogen	4–10	4–9	5–8	4–9	8–13	12–20
Phosphorus	1–1	0–1	0–1	1–2	1–2	1–3
Potassium	15–27	7–15	7–17	13–27	9–18	8–12

[a]Values do not include leaves, which fall off and are mostly left in the field.

Crop residues contain small amounts of nutrients (Table 4.2) and the importance of recycling crop residues is to replenish soil organic matter and provide mulch. Cycling crop residues through composting or animals improves the availability of nutrients.

4.8 Use of improved germplasm

Improved germplasm means seeds, seedlings and other planting materials that have been bred to meet particular requirements of the environment in which they are to be grown. While almost all improved germplasm will produce higher yields than ‘local’ varieties, yield is not the only consideration, particularly when seeds are planted in the harsh environment found in many areas of SSA. Improved soil fertility management is usually required to gain the maximum benefit from investments in improved varieties. We will now review the characteristics of improved germplasm.

4.8.1 Genetic yield potential

An important trait in improved germplasm is high genetic yield potential when grown in the targeted biophysical environment. Improved crop varieties are often tailored to meet the specific environmental conditions (e.g. temperature, humidity, soil acidity) found in the targeted farmers’ fields. In most improved germplasm the proportion of total biomass converted into the harvested part (e.g. grain, tuber), referred to as the harvest index (HI) is greater than in local varieties.

Over the past 10 years improved germplasm has been produced with additional traits such as:

- rice with high vitamin A content;
- high-quality protein maize;
- yellow starch potato rich in vitamin A; and
- flood-tolerant rice.

Breeders often produce materials that are adapted to or tolerant of particular environmental stresses such as aluminium toxicity, the lower temperatures found at high altitude, or drought.

4.8.2 Pest and disease resistance

Pest and diseases make crop plants unhealthy and results in crop loss or even crop failure. Unhealthy plants are not able to recover nutrients from the soil effectively so crops affected by pests and diseases result in wasteful and inefficient use of fertilizer and other inputs. Pest and disease resistance is often incorporated in modern varieties to complement traits for high yield, but it is important to remember that plant health and resistance to pests and diseases is also improved when crops are supplied with adequate nutrients.

Some improved planting materials are simply disease-free materials such as virus-free cassava cuttings and disease-free banana plants, both produced by tissue culture. There are also genetically modified organism (GMO) planting materials such as GM cotton with pest resistance that have been adopted in SSA.

4.8.3 Nutrient use efficiency

Because improved varieties usually have a larger harvest index they also usually have higher agronomic efficiency compared with ‘local’ varieties.

Some improved varieties have more extensive or deeper root systems that enable the crop plants to scavenge nutrients from a larger volume of the soil compared with local varieties.

4.8.4 Availability and quality of planting materials

Farmers need to be able to purchase improved varieties, either commercially through agro-dealers or other input supply networks, or through local, community-based seed multiplication efforts. Continuity of supply is also obviously very important. It is important that the quality of material offered to farmers meets minimum standards:

- of purity (i.e. the seed, cuttings or plants conform to type);
- is free of diseases and pests;
- is uniform in size; and
- has high viability (for seed measured as the germination rate).

4.8.5 Finding and selecting improved germplasm for use in ISFM

It is important to have information about the currently available improved varieties for a particular region, where these can be purchased, and their price. It is also important to investigate existing community-based seed production systems since improved varieties for certain crops, especially legumes, may not be available from commercial sources.

Before their introduction, new varieties must be carefully tested in the environment in which they are to be released for use. As part of the assessment, new varieties should be assessed for vegetative growth, pest and disease resistance, drought tolerance, eating and storage properties postharvest, as well as yield.

4.9 Harnessing the benefits of N_2-fixing legumes

Although many crops are starved of N when growing in poor soils, they are surrounded by air that is 79% nitrogen (N_2) gas. Legumes have evolved the ability to capture N_2 gas from the atmosphere by forming nodules with soil-inhabiting bacteria called rhizobia. The legume plant supplies the rhizobia with energy as carbon from photosynthesis, and in return the rhizobia fix N_2 gas into a form of combined N that is released into the root nodule and used by the plant for growth.

Legumes have leaves and seeds that are rich in protein N, which explains why they are important in agriculture. Legumes are widely used for:

- **Food.** This includes grain legumes or pulses such as the pea (*Pisum sativum*), common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*) and pigeonpea (*Cajanus cajan*). Groundnut (*Arachis hypogaea*) and soybean (*Glycine max*) have grain rich in both protein and oil.
- **Fodder.** The foliage of many herbaceous legumes (e.g. *Stylosanthes guianensis*, *Desmodium uncinatum*) and shrubs (e.g. *Calliandra calothyrsus*, *Gliricidia sepium*) forms excellent fodder for livestock.
- **Fuelwood and poles.** Many fast-growing legume trees are useful as wood for fuel, fencing and stakes and other purposes (e.g. *G. sepium*, *Acacia* spp.)
- **Fertility.** All legumes mentioned above have the potential to improve soil fertility, but the largest benefits are found with green manure legumes (e.g. *Mucuna pruriens*, *Calopogonium mucunoides*), grain legumes and fast-growing shrubs or trees (e.g. *G. sepium*, *Sesbania sesban*) when they are grown in rotation with crops or as intercrops to improve soil fertility (see Box 4.1).

Some of the most successful legumes have multiple uses – and are termed multi-purpose legumes.

Box 4.1 Benefits and costs of green manures and tree legumes

Despite intensive research and development projects that have promoted the use of green manure and legume trees (the so-called 'fertilizer trees') for soil fertility improvement in SSA, uptake has been disappointing. The investment required to prepare land, sow, weed and plough under a green manure or tree legume is considerable, particularly given that the benefit of increased yield is realized only at the end of the growth of the subsequent crop, sometimes more than a year later.

A rule-of-thumb is that a green manure legume must yield at least 2 t/ha dry matter or roughly 50–60 kg N/ha – which is likely to give an extra 1 t/ha of grain in the following cereal crop, to take into account the potential loss of land productivity. Even then this may not repay the extra labour investment required.

Although claims have been made of fertilizer trees being used by hundreds of thousands of farmers, these trees disappeared within a couple of years from the farming systems where they were promoted since the projects ended. The planting of the improved fallow trees by farmers has since proved to be pseudo-adoption – effectively farmers producing legume tree seed for a lucrative market provided by the NGOs and research institutes. This is not a sole case. There are many examples with green manures and legume trees for soil fertility improvement, which predated the ICRAF example, where similar patterns of rapid expansion were observed during the projects when legume seed was in high demand, and then dis-adoption after the project ended.

Participatory evaluations of legume technologies for soil fertility improvement conducted with smallholder farmers in Ghana, Kenya, Uganda and Zimbabwe indicate that farmers value most legumes that give direct benefits of food, cash income or fodder for animals. Benefits of legumes in terms of soil fertility improvement are recognized, but regarded to be of secondary importance.

There may be niches where green manures and legume trees for soil fertility improvement are welcomed and used by farmers. There are examples where green manures achieved spontaneous diffusion in smallholder agriculture in the tropics where they gave labour savings through suppression of pernicious weeds. Such niches need to be identified in a truly participatory manner with strong feedback from farmers and comparison with alternative approaches to soil fertility improvement.

4.9.1 The components of a successful N_2-fixing symbiosis

Successful N_2-fixation by legumes (Box 4.2) in the field depends on the interaction:

$$(G_l \times G_r) \times E \times M$$

where:

- G_l is the legume genotype (the species being cultivated).
- G_r is the strains of rhizobium found in the soil or used to inoculate the legume genotype.
- E is the environment, i.e. the climate (temperature, rainfall, day length, etc. to encompass length of growing season) and soils (acidity, Al toxicity, limiting nutrients, etc.).
- M is the management, i.e. aspects of agronomic management (use of mineral fertilizers, inoculation, sowing dates, plant density, weeding).

The establishment of effective N_2-fixation depends on optimizing all of these components at the same time.

Legumes are often women's crops, grown for home consumption. They are often grown in poorer soils with little application of fertilizers or manure, and with less attention in terms of labour for crop management. This means that E and M often override the potential of the legume–rhizobium symbiosis for N_2-fixation. In such circumstances, opportunities need to be sought for including legumes in rotation with other crops such as cereals that receive fertilizer so that the legume can benefit from the residual nutrients in the soil. Where there are market opportunities for grain legumes, direct use of basal fertilizer on legumes may be appropriate and necessary to achieve good yields. The nutrient most commonly required by legumes is P, but increasingly deficiencies of K and other nutrients are observed in the field.

4.9.2 The need for inoculation with rhizobia

Legumes vary widely in their ability to form root nodules with 'indigenous' rhizobia – i.e. compatible rhizobia commonly found in the soils where the legumes are grown:

- Soybean (*G. max*) and chickpea (*Cicer arietinum*) nodulate with a restricted number of rhizobial strains or species and are thus considered as 'specific' in their rhizobia requirement.
- Cowpea (*V. unguiculata*) is considered the most promiscuous (non-specific or naturally nodulating) of the grain legumes, and nodulates with a wide range of rhizobia found in many soils.

In nature there is a huge range of promiscuity and specificity, but the most common state is for legumes to be promiscuous in nodulation with indigenous strains in the soil. Thus grain legumes such as cowpea and groundnut, and the vast majority of fodder, green manure and tree legumes do not need to be inoculated with rhizobia.

Legumes that have a specific requirement for rhizobia, particularly soybean and chickpea, need inoculation. Rhizobial inoculants are applied on the seed at planting (see http://www.n2africa.org/N2media for a series of educational videos on inoculant manufacture and use).

Most rhizobial inoculants are used with soybean, and on poor soils they can make the difference between crop success and failure. Most varieties of soybean are specific in their requirement for rhizobia and need to be inoculated to get good yields. Newer (and some old) soybean varieties are promiscuous in their nodulation, but although they can form nodules and fix N_2 with indigenous rhizobia, inoculation still often increases their yield by up to 20%.

Although little research has been done on inoculation with chickpea in Africa, the available evidence suggests that this crop responds strongly to rhizobial inoculants. The situation with common bean (*P. vulgaris*) is less clear – most experimental results indicate small and highly sporadic responses to inoculants, though some scientists recommend inoculation with rhizobia.

Three situations occur where legumes generally do need inoculation:

- where compatible rhizobia are absent from the soil;
- where the population of compatible rhizobia is small; and
- where the indigenous rhizobia are less effective in fixing N_2 with the legume compared with selected inoculant strains.

Although inoculation may give increased yields in the first season with newly introduced legumes where they have never been previously grown, some compatible rhizobia are often present. These rhizobia will multiply in the rhizosphere of a compatible host so that the population builds up and inoculation is not essential in subsequent seasons. If inoculants are available they are not costly compared with other production inputs like fertilizer, so that using inoculants is preferable to risking a loss in yield.

New research with high-quality inoculants indicates that yield gains through inoculation could be possible even with the most promiscuous legumes in the longer term.

4.9.3 Legume contributions to soil fertility

Biological N_2-fixation can contribute as much as 300 kg N/ha in a season in grain legumes or legume green manures and exceptionally as much as 600 kg N/ha in a year in tree legumes. But where constraints such as drought or deficiencies in P or K limit legume productivity, inputs from N_2-fixation are also reduced.

The contribution of legumes to soil fertility depends on the amount of N_2-fixed in relation to the amount of N taken from the field at harvest time. Legumes grown for soil fertility improvement, such as green manures or agroforestry trees, add the largest amount of N as little is removed from the field (see Box 4.2). There are large differences between grain legumes in the amounts of N returned to the soil. In general the greater the biomass produced, the larger the inputs from N_2-fixation – so the multi-purpose soybean varieties, or the creeping varieties of groundnut and cowpea leave behind the most N.

Box 4.2 Nodulation in the legume family (the *Leguminosae*)

The *Leguminosae* contains roughly 19,000 species that are classified into three sub-families: the *Caesalpiniodeae*, the *Mimosoideae* and the *Papilionoideae*. The *Caesalpiniodeae* is considered to be the oldest and ancestral subfamily from which the other sub-families diverged. The vast majority of legumes in the *Mimosoideae* and the *Papilionoideae* are able to form root nodules and fix N_2 gas, but only a quarter of the caesalpiniod legume species can nodulate and fix N_2. One well-known example of a N_2-fixing caesalpiniod legume is the forage legume, Wynn cassia (*Chamaecrista rotundifolia*). Some non-nodulating legumes are widely planted as ornamentals (e.g. *Bauhinia* spp., *Delonix regia*) or are used as agroforestry trees (e.g. *Senna siamea*, *Senna spectabilis*) as they grow fast and provide shade and fuelwood. Under some circumstances *Senna* spp. have been observed to be suitable for rehabilitation of degraded soils. In Benin, the deep rooting of *S. siamea* allowed it to recover nutrients from deep soil horizons that were not explored by other legume trees provided there was a relatively rich subsoil.

In southern Malawi a 'food for work' programme in the early 1990s led to the extension and recommendation of alley cropping to more than 100,000 farmers. Many farmers were supplied with seedlings of *S. spectabilis*. Unfortunately, benefits were minimal on the infertile soils of smallholder farmers' fields and yields were no better or even worse than without trees. The reason that *Senna* was promoted in Malawi was largely due to the lack of sufficient supplies of seed of other N_2-fixing legume trees such as *Gliricidia sepium*. Thus although non-N_2-fixing legumes can sometimes be beneficial for soil fertility, it is dangerous to assume that this is due to inputs from N_2-fixation.

If all of the legume residues are removed from the field at harvest the amount of N returned to the soil from the legume may be small. Often legume residues are removed from the field and fed to livestock. This is often the case with groundnut where the whole plant is pulled from the soil and pods are shelled at the homestead. Short-duration varieties of legumes such as soybean and cowpea which are harvested when the pods have dried in the field have already lost most of their leaves through senescence and these leaves, as well as the roots and nodules are left in the soil and provide N for the subsequent crop. In the Sahel, some farmers sell cowpea hay as a cash crop and, as a result, all the nutrients in the above-ground biomass are 'lost' form the field – but the cash from cowpea hay might be used by the farmer to purchase fertilizer for use on other crops.

Yields of maize grown after grain legumes can be double those of maize grown year after year on the same plot. Some of the benefits of crop rotation cannot be ascribed directly to inputs from N_2-fixation but are due to benefits of disease and pest suppression by breaking the continuous monoculture of maize.

Many grain legumes are grown as intercrops with cereals, and other opportunities exist such as intercropping legumes during the establishment of widely spaced crops such as cassava. When intercropped, the benefits of growing N_2-fixing legumes are more in the additional crop provided, and in the 'sparing' of N for the cereal rather than a direct input of fixed N_2 into the soil.

4.10 Use of arbuscular mycorrhizal fungi (AMF) inoculants

Arbuscular mycorrhizal fungi (AMF) are beneficial organisms that can be prepared as commercial products and are used widely in agriculture. Plants vary in their response to mycorrhiza with some species being entirely dependent (obligate), partially dependent (facultative) or non-responsive. Commercial inoculants of AMF are available in the market and have been used to increase plant productivity in agriculture, forestry and land restoration schemes. AMF form an effective association with more than 80% of economically important crops and enhance nutrient and water uptake, reduce pest and disease damage and improve soil structure. Mycorrhizal propagules are present in all soils but inoculation may be beneficial where the indigenous population is small.

AMF work best in low-fertility status soils and particularly in soils containing small amounts of P. AMF are not a *substitute* for fertilizer and in low P status soils, application of P fertilizer is required before a response to AMF inoclulation is obtained.

P has low mobility in soil and P supply is rapidly depleted by crops in the root zone. AMF hyphae improve root access to P and other nutrients such as zinc in the soil beyond the depletion zone surrounding the crop's roots.

AMF products function best under the following conditions:

- soils where severe and erosion has resulted in top soil loss;
- low-input cropping where little mineral fertilizer has been used;
- crops established after bare fallow where the population of AMF propagules is small due to absence of host plants;
- land use with non-mycorrhizal plant species such as brassicas; and
- non-responsive soils (i.e. soils that respond poorly to fertilizer application).

Plant characteristics favourable for AMF establishment are:

- plant species with poor root development;
- nodulating legumes which have high P demand for nodulation;
- vegetatively propagated plants (e.g. root tubers, plantains, bananas, tree species cuttings) with poor root development; and
- plants raised under nursery conditions prior to field establishment.

High-quality commercial AMF products have the following properties:

- a high count of viable and infective propagules (spores, hyphae and infected root fragments) present in the product; and
- the ability to colonize the host with arbuscules and vesicles evident in the roots of host plants.

Inoculation may not provide a response if:

- soils are fertile and contain an ample supply of P;
- the host is not dependent on mycorrhiza association; and
- soils have inherently high AMF-infective propagules.

4.11 Other soil fertility management practices

Other measures are often needed besides the use of suitable germplasm, fertilizers and organic inputs, particularly if there are other soil fertility constraints that prevent good crop growth. Some examples are given below, recognizing that this list is not necessarily complete:

- **Soil acidity correction**. Some soils are strongly acid, either because of inherent soil properties or due to long-term acidity-inducing management practices (e.g. the long-term use of ammonium-based fertilizer). Acidity in itself is often not the major problem, unless the pH is very low (e.g. <4) but acid soils often have high exchangeable Al contents which severely restrict the growth of some crops (e.g. maize). Lime application rates should be calculated to reduce exchangeable Al (to about 15%) rather than increasing soil pH.
- **Micronutrient deficiencies**. Deficiencies to particular micronutrients may be observed (e.g. Zn, B). Such deficiencies are often expressed during plant growth. Some fertilizer blends such as Mavuno fertilizer in Kenya contain micronutrients.
- **Breaking hardpans**. Continuous management on soils that are prone to compaction can result in a sub-surface soil barrier to crop root growth. Breaking such hardpans by deep ploughing or chisel ploughing to a depth of up to 30 cm allows roots to penetrate the hardpan and access more nutrients and water, resulting in better crop growth.
- **Water harvesting**. Nutrients will only be recovered efficiently if the crop has sufficient water. The amount of rainfall captured and made available to crops can be increased in areas that are prone to drought. Most approaches aim to harvest extra water by installing structures that decrease runoff (e.g. the Zaï system used in the Sahel or the use of planting basins in southern Africa), or by maintaining organic mulch on the soil surface to promote infiltration and reduce evaporation from the soil surface. All such practices require extra resources

in terms of labour or organic materials and an assessment of the risk of drought stress in a particular area will determine whether the deployment of these extra resources is worthwhile.

- **Erosion control.** Soil erosion can be a serious problem, especially on fields with steep slopes, but also on slightly sloping fields with coarse-textured top soil that is prone to erosion. Soil organic matter and nutrients are lost in eroded soil, which may substantially reduce the agronomic efficiency of applied inputs. Several measures can assist in controlling erosion, including planting of live barriers (e.g. grass strips), construction of terraces, or surface mulch application.
- **Land preparation.** Appropriate seedbed preparation is a prerequisite to achieve good crop establishment, particularly with crops that produce small seeds. Germination is improved (and seed requirements may be reduced) when the top soil is cultivated to produce a tilth comprising small particles.
- **Planting date.** A delay in planting date usually affects yields negatively, particularly where the growing season is short. Planting date should be selected based on knowledge of the onset of the rainy season. Early planting is generally a prerequisite for achieving high yields.
- **Spacing.** When crops are planted together, they compete with each other for nutrients, light and water. Appropriate planting densities, expressed as the number of plants per hectare need to be adjusted for different environments and these are often reduced when rainfall and soil fertility conditions are suboptimal (Table 7.40). For instance, when grown as monocrops, maize is recommended to be planted at about 50,000 plants/ha while soybean is better planted at about 300,000 plants/ha. It is also important to consider the distance between planting rows, the distance between plants within a row, and the number of plants per planting hole.
- **Planting practices.** Seed viability should be at least 80% to achieve a full crop stand. Seeds of cereals and grain legume crops should be planted at the correct depth. More seeds than required to reach the optimal planting density are planted to allow for thinning and incomplete germination. Cassava cuttings should be inserted into the soil at the correct angle. The size of the tuber is important for other root crops (e.g. yam, potato, *Solanum tuberosum*).
- **Weeding.** Weeds compete with crops for nutrients, water and light, and their timely removal has a substantial impact on crop yield. It is also important to weed before applying top-dressed fertilizer so that the nutrients applied benefit the crop and not weed growth.
- **Pest and disease management.** Pests and diseases must be controlled at specific crop growth stages. Treated seed should be used where there is a risk of pest attack in the seedbed. In many crops, pest and disease control will be required, usually between flowering and pod or grain filling. Failing to do so will result in an unhealthy crop that will use nutrients and water inefficiently.
- **Intercropping.** In many cropping systems in SSA, different crops are ‘intercropped’ or planted in the same plot of land at the same time. Such intercropping arrangements need to take into account the specific growth features and needs of the individual crops to minimize intercrop competition. Sometimes the planting of one of the intercrops is delayed to minimize competition. For instance, while beans can be intercropped with maize effectively at normal maize spacing, the maize spacing should be increased (i.e. fewer plants per hectare) when intercropped with soybean, which requires relatively more space compared with beans. Legumes can be intercropped with cassava relatively easily provided the spacing of cassava is slightly reduced to allow the legumes to grow well and minimize intercrop competition. Obviously, specific crop management practices in intercrops need to be adapted to the needs of each crop in terms of spacing, nutrient management, relative planting dates, or pest and diseases control practices.

4.11.1 Conservation agriculture (CA): a silver bullet?

Conservation agriculture (CA) is underpinned by three basic principles:

- Soil disturbance is minimized by reduced or zero-tillage.
- The soil is kept covered with organic materials (crop harvest residues or cover crops) – at least 30% soil cover.
- Crop rotations/associations are used.

All three principles are important possible *options* for use in ISFM but, as with all techniques, their use should depend on a case-by-case assessment of local requirements as part of local adaptation. CA provides a number of advantages, including:

- rapid planting of large areas; and
- reduction or elimination of soil erosion.

A number of pitfalls have been encountered, however, when full CA implementation has been attempted without sufficient local adaptation:

- There may be insufficient crop residues available for mulching where they provide greater returns for the farmer over the short term when used as animal feed.
- CA often results in short-term decreases in crop yields, and significant crop yield increases are only achieved in the long term.
- CA may increase labour requirements unless herbicides are available and are cost effective for weed control.
- Full CA requires a fundamental change in the farming system, which may not be practical or economical for the farmer.

In addition, the potential to build up soil organic carbon depends on soil texture (particularly clay content) and the extent to which the soil's capacity to store carbon has already been reached.

CA may not result in improved agronomic efficiency (AE) of fertilizer use. AE may even be reduced under prolonged CA due to increased leaching because of increased water infiltration and a more continuous macropore system in the soil.

4.12 Organic agriculture

Organic agriculture, low-input agriculture and evergreen agriculture emphasize reliance on organic resources to provide nutrients to sustain soil fertility and produce economic yields of crops. Such techniques may at first appear attractive because they suggest that it is possible to produce economic yields of crops without mineral fertilizer use.

Extensive research has shown that, apart from specific cases where production for niche markets is possible, mineral fertilizers are an essential component in sustainable agriculture because:

- Nutrient stocks in soils in many parts of SSA have already become depleted and require replenishment.
- Farmers lack sufficient quantities of organic resources to replenish and sustain nutrient stocks in soils.
- Large and economic responses to mineral fertilizer are obtained over much of SSA.
- Organic resources are bulky and their management is labour intensive. Application of large quantities of organic resources is often insufficient to overcome nutrient deficiencies.

ISFM advocates the use of mineral fertilizers *in combination* with organic resources because research has shown that their combined use provides greater benefits than the sole use of either organic resources or mineral fertilizer.

4.13 Adaptiveness of interventions

In the end, the adoption of all practices is governed by the fit of technical performance (P) at the field scale, opportunities and trade-offs (T) at the farm and village scale, and farming systems context (C) at the regional scale. Adoption should take account of technology performance, trade-offs with other options, and relevance to the particular farming system as well as consideration of interactions between these three elements (Figure 4.3).

Adoption = Performance + Trade-offs + Context + (PTC)

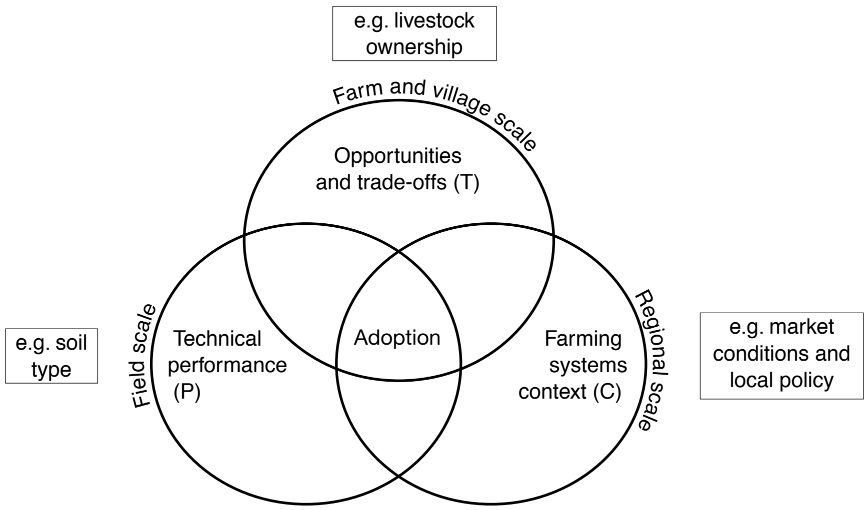


Figure 4.3 A number of pre-conditions must be met before conservation agriculture (CA) can be adopted profitably by farmers in a particular locality.

4.14 Economics

Soil capital is the farmer's most important productive asset. Farmers make use of this asset by combining it with variable inputs like labour, seeds, fertilizers and organic inputs in order to produce output of a particular crop for food, income or raw material for other production processes.

Capital is simply defined as cash, goods or property used to generate income. In the case of 'soil capital', a farmer will have to spend more on other inputs to maintain his/her output if his/her soil capital declines. Soil capital consists of several properties, such as nutrient content (i.e. fertility), organic matter, moisture and living organisms, all of which change over time and are unevenly distributed across farms and down the soil profile. Therefore maintaining this capital resource demands addressing and maintaining all the properties of the resource.

As with other types of farm capital (e.g. agricultural equipment), the farmer incurs costs to maintain soil capital and there are two primary cost components:

- **Direct costs** are the costs to the farmer of the effort (i.e. labour), materials (e.g. fertilizer), equipment and physical structures that are required to maintain or improve soil capital.
- **Indirect costs** (or output foregone) include any loss of future output that results from loss of soil capital due to present use of suboptimal soil practices.

The direct costs are easily assessed by a farmer because they involve direct expenditure on labour, materials and equipment. However, indirect costs are long term and not easily assessed. The benefits from investing in the soil capital are also twofold:

- The short-run benefits from annual crop harvests which represent a source of income and can also be used to reinvest in subsequent years by purchasing fertilizer, or paying for labour to construct soil and water conservation structures.
- The long-run benefits will be increased or maintained yield in the future due to soil quality, maintenance or improvement.

Therefore, making decisions about maintaining soil capital requires a dynamic, complex assessment of both the short-run, direct and the long-run, indirect costs and benefits. For purposes of illustration, it is useful to look at the case of soil capital in a typical farmer's soil and what can happen to that capital over time with continuous maize cultivation (Tables 4.3 and 4.4).

Table 4.3 Continuous maize production without ISFM.

Parameter	Units	Year				
		1	2	3	4	5
Available N in soil	kg/ha	60	30	15	7	4
Uptake of N by maize without use of fertilizer	kg/ha	30	15	8	3	2
Yield without fertilizer use	kg/ha	1000	900	700	500	350
Value of yield decline (initial yield – current yield x market price of maize[a])	$	0	40	120	200	260
Net benefit (yield × price – indirect costs due to decline in yield)	$	400	320	160	0	–120

[a]Maize price = $0.40/kg.

Table 4.4 Continuous maize production with ISFM.

Parameter	Units	Year				
		1	2	3	4	5
Available N in soil	kg/ha	60	60	60	60	60
Uptake of N by maize without use of fertilizer	kg/ha	30	30	30	30	30
Fertilizer input (replacing the N depletion)	kg/ha	23	23	23	23	23
Organic manure input (replenishing organic matter and N)	kg/ha	7	7	7	7	7
Yield with fertilizer and manure use	kg/ha	1100	1100	1100	1100	1100
Manure (labour for collection)	$/ha	20	20	20	20	20
Fertilizer	$/ha	25	25	25	25	25
Net benefit (yield × price[a]) – direct costs		395	395	395	395	395

[a]Maize price = $0.40/kg, fertilizer = $0.5/kg.

Without ISFM, soil capital in the form of inherent N declines annually under maize cultivation over a period of 5 years. For simplicity sake we assume total N in the soil is 60 kg/ha and that maize can utilize 30 kg N/ha in the first season, but as the N content reduces, the crop takes up less N in subsequent years (Table 4.3). We can also assume that natural replacement of N is negligible hence the stock of N reduces with each year of cultivation. The indirect cost of this decline in soil capital is a cumulative yield loss of 1550 kg of maize over what could have been produced had the N capital been maintained. Assuming a price of $0.40/kg of maize, the total loss over the 5-year period would be $620.

Where a farmer applies ISFM, adding organic residues and mineral fertilizer to the soil during the 5-year period (Table 4.4), assuming a 50 kg bag of urea (46% N, 23 kg N/ha) and 1 t of organic manure are applied to the soil at a cost of $45/year ($225 for 5 years), the cost of maintenance in this particular situation is less than the indirect cost from reduction on yield ($620) as a result of the N depletion shown in the previous table (Table 4.3). This illustrates that over time, the maintenance of soil capital can yield greater profit than allowing the capital to decline. The application of inorganic fertilizer and manure also increases the yield in the first year. Therefore the use of the inputs has a double effect of first increasing yield and second maintaining soil fertility, thus sustaining output over time.

From the farmer's point of view, two major constraints affect the ability to invest in soil capital:

- the cost of inputs; and
- the value of output.

However, if the value of the output is less than the cost of inputs in a given year, the farmer can experience a loss. In the long run though, if what is being mined (e.g. nutrients from the soil) is more than what is being invested, the capital will decline in value, yield will decline and aggregate income over time will be less than where fertilizers and manure are used.

Because subsistence farmers aim to maximize food production rather than income, they are unlikely to have sufficient cash resources to invest in maintaining soil capital. Commercial farmers producing cash crops are more likely to have the cash resources as well as the incentive to invest in soil capital.

4.15 Conclusions

In this section we have:

- reviewed in detail the use of organic and mineral fertilizer inputs;
- identified a variety of practices that help or maintain soil capital;
- assessed ways to measure nutrient use efficiency and methods to prevent losses; and
- reviewed the economics of adoption.

In the next section we will discuss the implementation of ISFM in detail.

4.16 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

Giller K. (2000) Translating science into action for agricultural development in the tropics: an example from decomposition studies. *Applied Soil Ecology* 14, 1–3.

Figures 4.1 and 4.2 are presented and discussed in these two articles.

Giller, K.E. (2001) *Nitrogen Fixation in Tropical Cropping Systems*. CAB International, Wallingford, UK.

In addition to the comprehensive background text see www.N2Africa.org *for many learning materials on nitrogen fixation by legumes.*

Giller, K.E., Cadisch, G. and Palm, C.A. (2002) The North–South divide! Organic wastes, or resources for nutrient management? *Agronomie* 22, 703–709.

Giller, K.E., Witter, E., Corbeels, M. and Tittonell, P. (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field Crops Research* 114, 23–34.

The potential benefits of conservation agriculture are discussed in relation to the constraints and opportunities faced by smallholder farmers.

Kamprath, E.J. (1970) Exchangeable aluminium as a criterion for liming leached mineral soils. *Soil Science Society of America Proceedings* 34, 252–254.

This classic article indicates that calculation of liming requirements of acid tropical soils should be based on reducing aluminium saturation to <15% rather than on changing soil pH.

Palm, C., Myers, R. and Nandwa, S. (1997) Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh, R.J., Sanchez, P.A. and Calhoun, F. (eds) Replenishing soil fertility in Africa. Soil Science Society of America, Indianapolis, Indiana, pp. 193–219.

The original graph for Figure 4.1 is presented and discussed here.

Palm, C.A., Gachengo, C.N., Delve, R.J., Cadisch, G. and Giller, K.E. (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems and Environment* 83, 27–42.

Palm, C.A., Giller, K.E., Mafongoya, P.L. and Swift, M.J. (2001) Management of organic matter in the tropics: translating theory into practice. *Nutrient Cycling in Agroecosystems* 61, 63–75.

These two articles describe the different roles of organic amendments in management of soil fertility in the tropics, in relation to the qualities and quantities of organic resources available.

Piha, M.I. (1993) Optimizing fertilizer use and practical rainfall capture in a semi-arid environment with variable rainfall. *Experimental Agriculture* 29, 405–415.

A practical approach to varying the rates of fertilizer used in relation to the amount of rain received during the growing season is presented.

Smaling, E.M.A., Stoorvogel, J.J. and Windmeijer, P.N. (1993) Calculating soil nutrient balances in Africa at different scales. II. District scale. *Fertilizer Research* 35, 237–250.

Stoorvogel, J.J., Smaling, E.M.A. and Janssen, B.H. (1993) Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. *Fertilizer Research* 35, 227–235.

Two classic papers that explain the use of nutrient balances and soil fertility depletion and how these relate to the sustainability of crop production.

Vanlauwe, B. and Giller, K.E. (2006) Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems and Environment* 116, 34–46.

Some common misunderstandings concerning soil fertility management are exploded in this general article. Essential reading for all involved in this field of development!

Photo 4.1 In western DRC, improved cassava germplasm (right) is a prerequisite to maximize the agronomic use efficiency of external inputs like fertilizer, since varieties susceptible to disease (in this case cassava virus) (left) do not provide a strong demand for nutrients.

Photo 4.2 Dual-purpose grain legumes produce a large amount of effective nodules and fix considerable amounts of N from the atmosphere.

Photo 4.3 Specific agronomic measures can increase system productivity in cassava-based systems in Sud-Kivu, eastern DRC.

Photo 4.4 Dual-purpose soybean varieties (right) provide more organic inputs and fix more N_2 gas from the atmosphere compared with short-duration specific varieties (left).

Photo 4.5 It may be possible to plant two short-duration soybean intercrops with cassava before the cassava leaf canopy closes.

Photo 4.6 Maize intercropped with soybean.

Photo 4.7 N fertilizer response trials on a smallholder farm on granite sands in Chinyika, Zimbabwe.

Photo 4.8 Effects of N fertilizer on maize productivity in N-deficient soils, and rotational effects of legumes.

Photo 4.9 An indirect effect of soil fertility improvement is improved tolerance of crop plants to striga infestation.

Photo 4.10 Delayed weeding will reduce the crop response to fertilizer in this intercrop of maize and pigeonpea in Western Kenya.

Photo 4.11 Maize intercropped with cowpea. The cowpea will be harvested after the maize crop.

Photo 4.12 Maize intercropped with cassava. The maize will be harvested before the cassava has matured.

Photo 4.13 Crop rotation and water conservation using tied ridges to enhance crop productivity.

Photo 4.14 Contour ploughing is an effective water management option for ISFM in semi-arid zones.

Photo 4.15 Farmers build bunds to manage soil on sloping land in Burundi.

Photo 4.16 Sloping land without bunds or terraces in south-west Uganda.

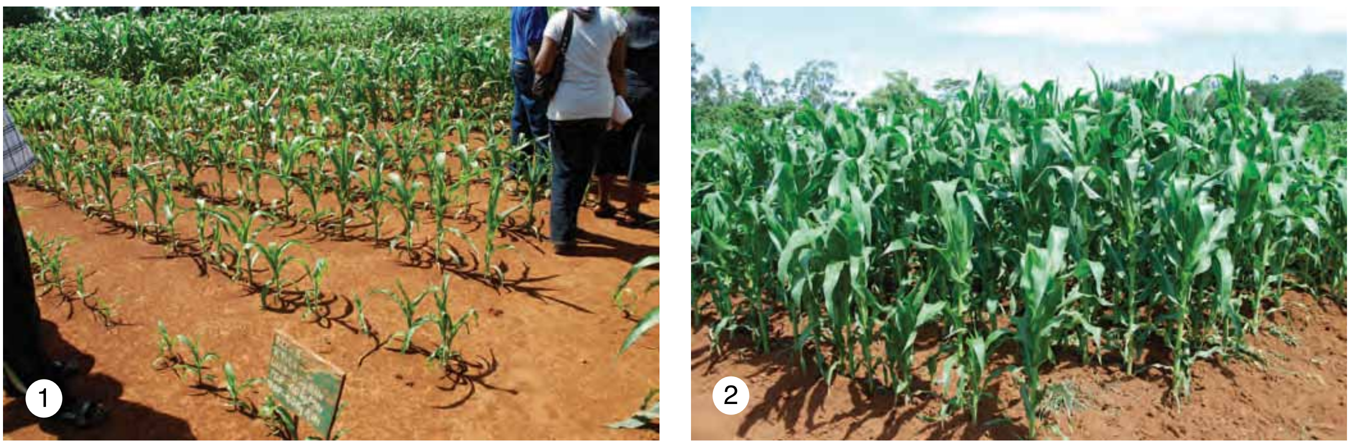


Photo 4.17 Maize planted without P fertilizer (1) is stunted compared with maize plants planted at the same time but provided with P fertilizer (2). Crops in both plots were supplied with sufficient N and K fertilizer. Maize growth is delayed by about 2 months when P fertilizer is not applied (1). Such stunting may go undetected, however, if there are no reference plots showing plant growth where nutrient deficiencies have been eliminated.

Photo 4.18 Both shoot and root development are better in the plant on the right that received P fertilizer.

Photo 4.19 This maize plant has already started flowering at a height of 40 cm, indicating very poor soil fertility and likely P deficiency.

Photo 4. 20 N deficiency in bananas in highland Uganda.

Photo 4. 21 A healthy and an N-deficient highland plant growing in a glasshouse.

Photo 4.22 Nutrient omission trials are a useful tool to assess the response to different nutrients in the field.

Photo 4.23 N deficiency in maize (foreground) and the effects of N fertilizer on maize growth (background).

Photo 4.24 A young maize plant showing clear P deficiency symptoms (1) including stunted growth (when compared with other plants that have received P fertilizer) and purplish colouring on leaves. The red-coloured maize leaves in older plants (2) were probably not caused by P deficiency.

Photo 4.25 K deficiency symptoms in soybean planted on K-deficient sandy soils derived from granite.

Photo 4.26 Multinutrient deficiencies may limit productivity in degraded soils. Here maize plants show Zn deficiency.

Photo 4.27 Crop residues and grass are applied as a mulch to the banana crop.

Photo 4.28 Nutrients contained in sugarcane stover left in the field after harvest will benefit the next crop.

Photo 4.29 In these fields in Rwanda, organic residues are piled in heaps before residues are applied.

Photo 4.30 A large load of maize including stover.

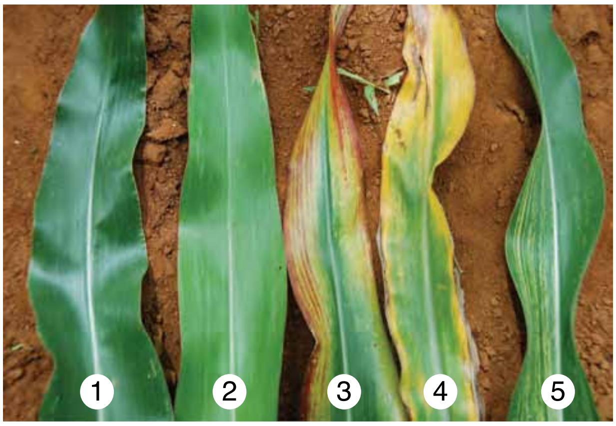


Photo 4.31 Nutrient deficiency symptoms are often visible on crop plants. A healthy leaf (1), compared with N-deficient (2), P-deficient (3), K-deficient (4) and diseased (5) maize leaves.

Photo 4.32 Cows inspecting improved forages in central Kenya.

Photo 4.33 Farmers construct mounds of soil for planting yams in Northern Ghana.

Photo 4.34 Over the long term, ISFM can contribute to increased resilience of crops to drought.

Photo 4.35 Fertilizer placed in a band adjacent to the crop row.

Photo 4.36 A soda-bottle cap contains about 6 g of fertilizer and is a useful measure for microdosing (i.e. applying small amounts of fertilizer).

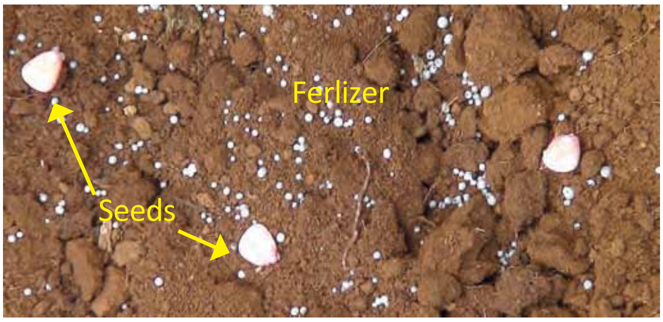


Photo 4.37 Incorrect placement of basal fertilizer at planting. Seed germination may be affected by 'fertilizer burn'.

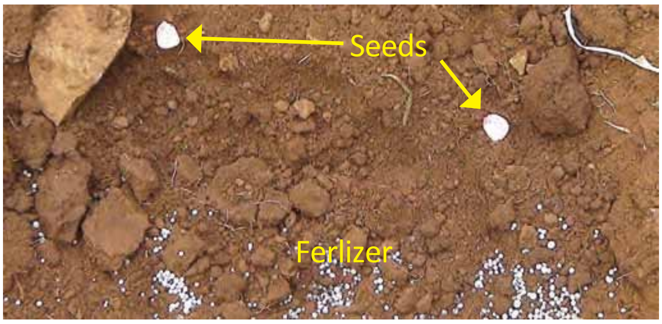


Photo 4.38 Fertilizer correctly applied in a band adjacent to seeds in the planting furrow eliminates to risk of 'fertilizer burn'.

Photo 4.39 Arbuscules formed by all arbuscular mycorrhizal fungi (AMF) species are intracellular sites of nutrient exchange between the host and the fungus.

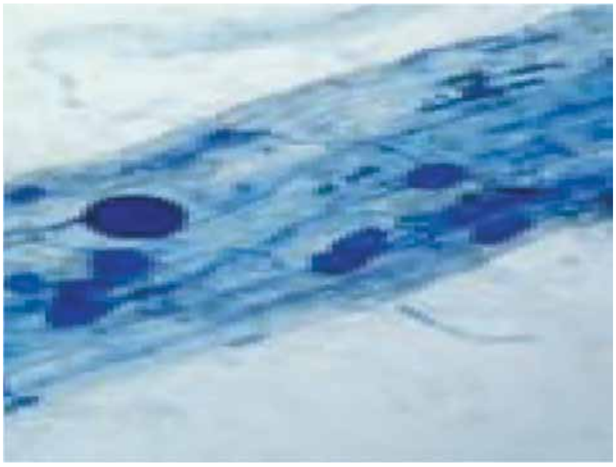


Photo 4.40 Vesicles formed by some AMF families are formed as storage structures with oily contents.

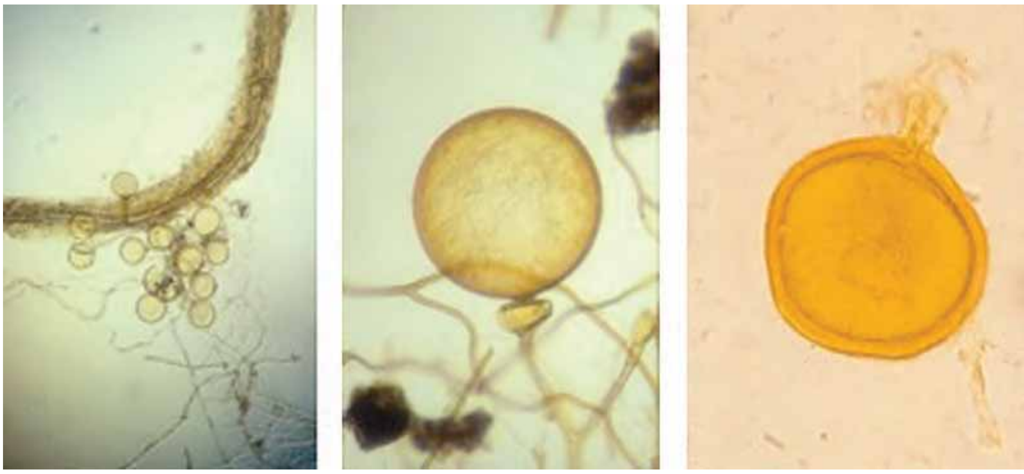


Photo 4.41 AMF spores in clusters outside (left) and in the plant root (middle and right). Spores can be formed singly or in clusters, may vary in size and be associated with a network of hyphae. They all comprise infective propagules.

Photo 4.42 Top dressing young maize plants with N fertilizer.

Photo 4.43 Fertilizer can be incorporated in the soil during weeding following top dressing.

Photo 4.44 Nodules are found on the roots of successfully inoculated legume plants. Nodules actively fixing N_2 gas are reddish-coloured inside.

5 Targeting ISFM options

5.1 Introduction

In Section 2 we explained the rationale and need for ISFM in the varied farming systems found in SSA. The principles of ISFM were outlined in Section 3 and common practices used in ISFM were detailed in Section 4. In this section we provide guidelines for targeting ISFM options within the diversity of African farms and farming systems. We assume that the reader is an extension worker employed by the government or an NGO that is working on productivity improvement in smallholder farming systems at district level in SSA.

From the outset, the extension worker must consider how he/she is going to scale up the implementation of ISFM in order to bring about large-scale change in his/her working area. At the same time, ISFM is a step-wise process for improving soil fertility. Little can be achieved in one season or even 1 year and the extension worker usually only achieves successful results by sustaining activities with client farmers over several years.

Even though the extension worker may be quite familiar with his/her particular working area, he/she will find it useful to conduct an analysis of the farming systems in that working area before starting any practical ISFM activities. Ideally, several extension workers team up and carry out farming systems analysis (FSA) in turn in their respective working areas. Bringing in an outsider's perspective often helps to reveal important characteristics of the farming system that may not be apparent to the local person.

Smallholder farming systems are found within diverse biophysical and socio-economic environments, and households develop different livelihood strategies according to the opportunities and constraints encountered in each environment. Within localities and villages, households differ in resource endowment (the amount of land and livestock they own), production orientation (food security versus food marketing) and objectives (survival versus profit), ethnicity, education, past experience, management skills and attitudes towards risks.

5.2 Farming systems analysis (FSA)

A farming system includes all components of a farm enterprise, including:

- cropland, cropping systems and livestock;
- common grazing land and wood lots managed by several farmers in a community; and
- off-farm activities.

All these components should be considered within a framework of markets for land, labour, production inputs, farm products, credit and knowledge.

FSA provides the information and data required to design, plan, implement, monitor and evaluate interventions to improve the productivity and sustainability of a particular farming system. FSA is used to identify 'domains', or groups of farmers with similar constraints and opportunities for improvement for whom extension workers can make more or less the same recommendation. FSA is therefore a useful tool for assessing opportunities for ISFM in farming systems in SSA (Figure 5.1).

An important output of FSA is the identification and characterization of the dominant farm and farming systems in the target area. This is important because scarce extension resources should be channelled towards the farm and farming systems where there is the greatest potential within the particular region or district to improve productivity and livelihoods by introducing ISFM.

The information resulting from FSA may be used by extension workers, agronomists, policy makers, economists or a multidisciplinary team of workers. Irrespective of the audience, the FSA should represent the reality faced by farmers in the respective locality.

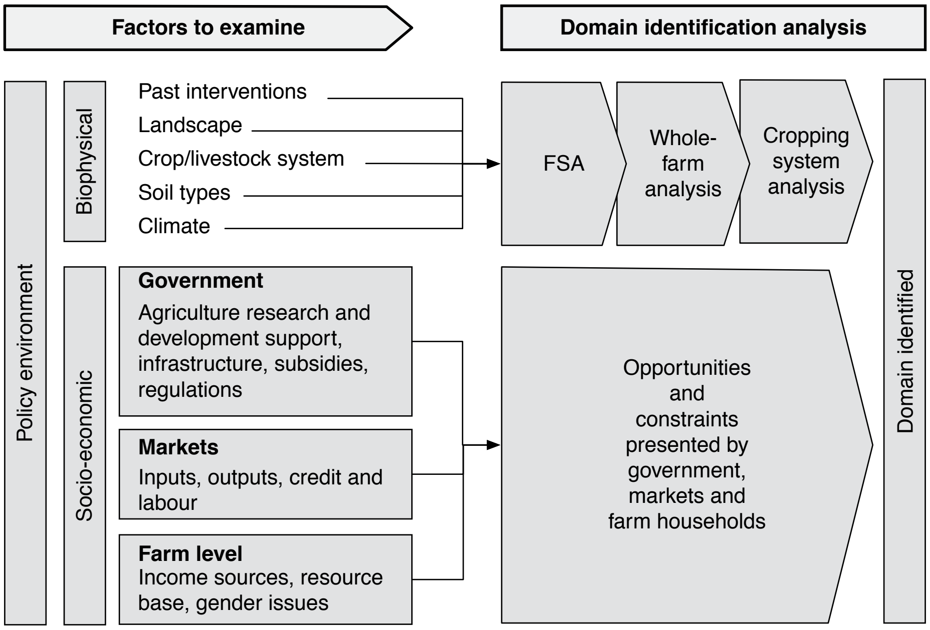


Figure 5.1 Farming systems analysis (FSA) involves a thorough analysis of the biophysical environment as well as socio-economic factors and aspects of policy that impact on farming. Opportunities and constraints are identified in the context of the farming and cropping systems investigated, leading to the identification of domains for field activities.

FSA should be carried out before starting any other field activities. It is often helpful to update the study each year to make an assessment of changes in the operating environment and as a result of project activities. Records of the FSA should be collated and stored in the district office so that others can use them in the future.

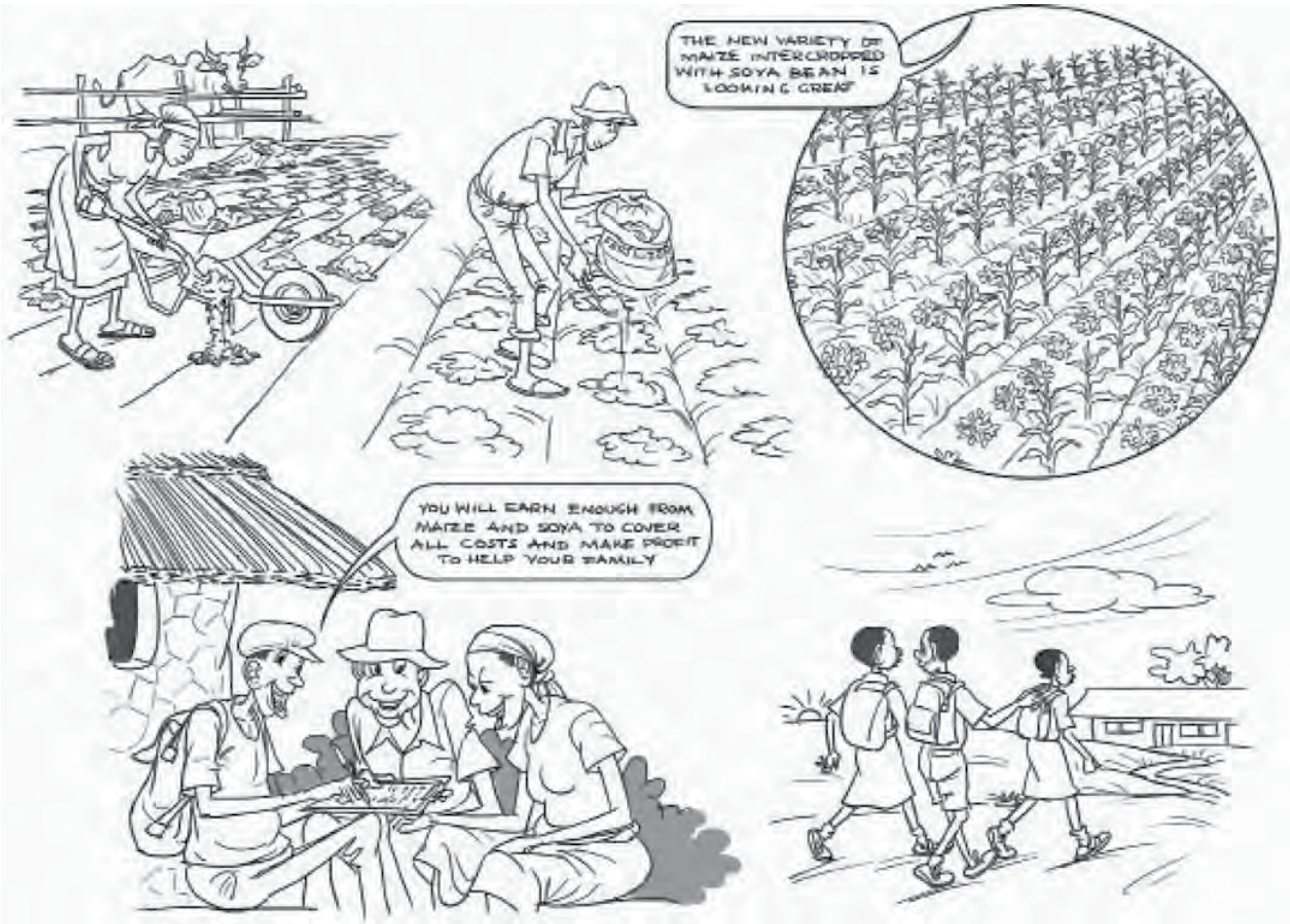
FSA should be carried out so that:

- The farmers are the subject not the object of investigation and participate fully in the study.
- The study captures the impact of gender on access to resources and markets, identifying opportunities and constraints to ISFM adoption associated with gender.
- The diversity of farming systems within a particular domain is captured and analysed.
- The study is not distorted by the time of year (season) when the investigations were carried out.
- 'Roadside bias' is avoided by walking over the area under investigation to gain an overview of the degree of heterogeneity within and between farms.

A properly designed and implemented FSA provides the following:

- identification of clusters of farm system types within the farming system;
- an assessment of the diversity in farm incomes and resource endowment in relation to clusters and opportunities for productivity improvement;
- a cropping calendar that shows the timing of key events including planting and harvest dates for the major crops within the farming system;
- quantitative information on the flows of services, farm products and nutrients within and between farms and farming systems;


LET'S BUY FERTILIZER TO MAKE OUR CROPS GROWN
NO WAIT!
LET'S BUY SOYA BEAN SEED, WE CAN GROW AND SELL THE BEANS
WE MUST BUY FERTILIZER
NO WE SHOULD BUY SOYA BEAN SEEDS
WELL, LETS FIRST LOOK AT THE FARM
THE CROPS CLOSE TO THE HOUSE LOOK MORE HEALTHY THAN THOSE FAR AWAY!
YES THIS IS WHERE I HAVE TIME FOR WEEDING
THE OUTER FIELDS ARE TOO FAR AWAY, WE SPEND LESS TIME THERE
SO LET'S THINK HOW WE CAN USE ISFM TO IMPROVE CROPS
INTEGRATED SOIL FERTILITY MANAGEMENT MEANS WE COMBINE DIFFERENT PRACTICES
SO WE SHOULD SPEND SOME OF OUR MONEY ON FERTILIZER AND SOME ON SOYA BEAN SEED
AND WE SHOULD BUY BETTER SEED AND USE SOME MANURE WHERE WE CAN
YES, AND WE MUST MAKE SURE YOU FOLLOW RECOMMENDATIONS ON SPACING AND TIMING
SO LETS GET GOING



- analysis of yield and productivity gaps in all the crop and livestock enterprises within the farming system;
- an assessment of the key risk areas in the farming system (e.g. weather, prices); and
- an assessment of the economics of the farming system including the identification of key drivers of change in productivity.

The FSA team will need:

- maps (soil, geology, vegetation, political and administrative boundaries);
- agriculture and other statistics for the local district office; and
- a global positioning system (GPS) device that provides the means to georeference and later map data points (e.g. farm locations, input suppliers).

We will now describe various activities that can be carried out as part of FSA.

5.2.1 History of past activities

It is very likely that there have already been various agriculture projects and programmes in a particular district. It is therefore important to find out about past interventions (government programmes, projects, farmer initiatives) to gain insights into the success and failure of past interventions.

5.2.2 Collection of biophysical data

Climate data help the team to understand the timing of events (land preparation, sowing, harvesting) and the risk involved in cropping systems. The most important information is rainfall (mm/month), raindays (number of rainy days per month) and data for the past 5 years are required so that it is possible to assess variability (mm/year, timing of the wet season). Other data (e.g. temperature, solar radiation, and wind speed and direction) are useful but not essential for ISFM-related activities.

Affordable and reliable electronic weather stations are now available and should be considered essential equipment in any medium-scale project.

Soil water deficits (mm/year) can be calculated based on rainfall data using a simple spreadsheet model.

5.2.3 Identification of dominant farming systems in each domain

Dominant farming systems can be found in most parts of SSA. For example, in a particular area farmers may grow a cereal (i.e. maize or rice) in rotation or intercropped with a grain legume crop. Crop residues are fed to livestock and animal manure is returned to the field. Within each farming system, however, we will likely find much variation:

- More wealthy farmers will have larger farms and will likely produce a surplus of crop products that can be sold in the local market. They are more likely to feed crop residues to their own livestock and may even purchase crop residues from surrounding smaller farms so that they can keep more livestock. The more wealthy farmers may already be using improved seed and fertilizer inputs.
- Poorer farmers usually have smaller farms that may not produce enough food to meet subsistence requirements. Crop residues may be sold to larger farms because the farmer cannot afford to purchase livestock. Poorer farmers often lack the cash resources to purchase inputs such as seed and fertilizer. Farming is often only a part of the household economy and family members may be engaged in off-farm income-generating activities or labour.

Thus, while wealthy and poor farmers may be encountering similar problems in terms of soil fertility management, the entry points for introducing improved ISFM practices and the time scale for farm improvement may be very different. Farmers do not belong in discrete groups of 'wealthy' and 'poor' farmers but rather we find continuous variation in terms of farmers so-called 'resource endowment'. Furthermore, soil fertility is not uniform within each farm but we may find more fertile fields close to the farmhouse and less fertile fields more distant from the farmhouse and depleted or degraded soils in common land.

5.2.4 Clustering farmers in groups

Most farm survey data show that there is considerable household diversity within a domain. Farmers can be grouped together in clusters according to the characteristics of their farm system, the contribution of off-farm activities to household income, and ownership of livestock. This helps extension workers to identify target groups and then plan activities and programmes designed to meet specific objectives (e.g. yield intensification on larger farms versus improved food security on smaller farms).

Key questions that should be included in surveys carried out for the purpose of 'clustering' might include the following:

1. Total area owned by the household (ha).
2. Total area farmed by the household (ha) including the area of 'in-fields', 'out-fields' and 'bush-fields'.
3. Total area with cash crops (ha).
4. Family size (number of members living and eating in the household).
5. Family labour (number of members working on the farm).
6. Family members working temporarily and permanently off-farm.
7. Age and educational level of the head of the household.
8. Percentage of household income derived from off- and non-farm activities.
9. Number of years receiving off-farm income.

10. Market orientation (percentage of production sold at market).
11. Number of local cattle.
12. Number of improved-breed cattle.
13. Number of oxen and ox-ploughs or other implements.
14. Total number of other livestock by type (sheep, goats, pigs, poultry).
15. Months of food self-sufficiency.

An example of a farm typology could be:

- **Type 1**: Farms that rely mainly on permanent off-farm employment.
- **Type 2**: Larger, wealthier farms growing cash crops on more fertile soils.
- **Type 3**: Medium resource endowment, food self-sufficient farms.
- **Type 4**: Medium to low resource endowment with low fertility status soils and wide variability in soil fertility within a farm and where farmhouseholds rely partly on non-farm activities for household income. Farmers own few livestock.
- **Type 5**: Poor households on low fertility status soils with wide variability in soil fertility. Family members are employed locally as agricultural labourers by wealthier farmers. Farmers own few livestock.

The past use of manure and fertilizer depends upon the resource endowment of the farmers and has a strong influence on the current soil fertility status of the farm. Thus the farm typology is important to assist in explaining variability in soil fertility. Farmers owning livestock are generally more wealthy than farmers without livestock.

5.2.5 Land:labour ratio

The ratio of land to labour can be calculated from the data collected for farmer categorization and clustering. For, example, in dryland farming, farmers could be separated into two groups based on the land-to-labour ratio:

- Farmhouseholds with a low land:labour ratio (i.e. <1 ha per household member) are more likely to have poor food self-sufficiency (<3 months) and to rely on off-farm activities for more than 50% of total income.
- Farmhouseholds with a high land:labour ratio (i.e. >1 ha per household member) are more likely to have better food security (>5 months) and to rely on off-farm activities for less than 50% of total income.

5.2.6 Assessment of risk

The FSA team should make an assessment of the major risk factors and rank them according to their influence on farm profitability. Major factors may include:

- drought during the main cropping season (frequency, magnitude, effect on crop yield);
- late rains (frequency, effect on crop yields);
- crop price volatility; and
- input prices and availability.

5.3 Cropping systems analysis

We will now describe various activities that can be carried out as part of cropping systems analysis.

5.3.1 Field inspection

This involves a thorough inspection of all the fields in a particular farm to gain an overall impression of soil fertility and its effects on crop production. Because a misleading picture may result from a single visit to a particular locality, several visits are probably required. An overnight stay in the locality, perhaps as a paying guest of a farming family can provide opportunities to gain insights that daytime visits may never reveal. An FSA team of four people can collect data for a farming system in about 5 days.

It is always important for NGOs to discuss FSA programmes with local government agencies before carrying out field work. Local government workers often have a deep knowledge of the local farming scene and past projects and initiatives.

Assess the variability of crop growth, appearance and yield in different fields within the farm to identify in-fields, out-fields and bush-fields.

During field inspections find out about the farmer's particular circumstances:

- Does he/she have livestock and use animal manures on his/her own farm or does he/she sell manures to other farmers?
- Are animal manures applied on all or only some fields or crops on his/her farm?
- Are crop residues left in the field, sold or used to feed the farmer's own animals?
- If the farmer does not own livestock, does he/she buy animal manures for use on his/her farm and, if so, on which fields are they applied?
- Does the farmer use mineral fertilizer and, if so, what types and quantities are used and which crops and fields are fertilized?

Field inspection should be carried out several times during a crop season because crop appearance changes over time. For example, a single visit that coincides with a short drought period will likely provide a misleading and incorrect impression of crop growth and soil fertility. Furthermore, several visits may be required before the farmer gains the confidence to reveal his/her situation and problems to visitors.

It is often helpful to make a map of the farm annotated with information about crop rotations, nutrient cycling, soil conditions and yields.

5.3.2 Estimation of yield gaps

An important step is to make an analysis of the difference between yields in researcher-managed on-farm trials where there are no agronomic constraints and yields in farmers' fields for all major crops in the cropping system. This provides an indication of the scope for improvement by introducing ISFM techniques. The FSA team should investigate the economics of closing yield gaps.

Agronomic trials may have been carried out in farmers' fields within the selected domain. Crop response trials provide useful information on the likely response to mineral fertilizers or other sources of nutrients and are key to assessment of soil fertility and required fertilizer application rates.

Estimate the yield of crops grown in 'in-fields', 'out-fields' and 'bush-fields'. Benchmark yields obtained in farmers' fields against the attainable yield for the respective crops grown without nutrient constraints. This can be done by reference to the results of on-farm agronomic trials, if available, or to the best crop yields obtained over the past few years in the specific region. Yield gaps provide an indication of the potential to improve yields and crop production by introducing ISFM practices.

5.3.3 Frequency and timing of visits

As mentioned above, a single visit often provides a distorted or unbalanced impression of crop growth in a particular farm. Extension workers should therefore carry out several field inspections to selected farms within a particular domain over the course of the growing season to gain a reliable insight into the effects of soil fertility on crop production.

Time field inspections to coincide with critical periods of crop growth. For example, soil fertility constraints are indicated if maize planted in soils adequately supplied with moisture are stunted 1 month after sowing.

5.3.4 Farm record keeping

Records of soil fertility and crop yields are seldom available yet extremely useful indirect information for the assessment of soil fertility. At the domain level, a log book maintained by village leaders that records crop yields provides useful information on the variability of yields across farms and over seasons and years.

A cropping system is an arrangement of crops within a specific field, planted following particular spatial and temporal arrangements and agronomic practices.

5.3.5 Use of a cropping calendar

A cropping calendar should be prepared that shows key events (i.e. dates of sowing, fertilizer application and harvesting) for each crop cultivated in each cropping system found in the area under study. Cropping calendars should be constructed in close cooperation with farmers and are important to capture variation among farmers in the timing of particular events.

The goal is to document existing practices as a first step in identifying possible entry points where improved techniques can be introduced. For example, a cropping calendar for a cereal crop may reveal the opportunity to improve the efficiency of N fertilizer use by timing application to coincide with periods of large crop nutrient demand.

5.3.6 Use of participatory budgeting

Field workers have found that instead of preparing a crop or enterprise budget *for* farmers it is more helpful to work *with* farmers to prepare budgets (Figures 5.2 and 5.3). So-called participatory budgeting is used to identify and quantify the use of inputs and the production of outputs for an enterprise over a given period of time. The method can also be used to explore the impact of introducing ISFM and to compare different ISFM options.

The method is based on an African board game sometimes called *Bao*, *Awari* or *Mancala*. Using a board or grid, or holes in the ground and seeds or small stones, farmers indicate different activities by placing symbols in the holes and indicate quantities of resources used or required with counters. For example, labour use for different farm enterprises can be quantified or a budget for a farm enterprise can be drawn up.

5.4 Soil fertility assessment

Soil fertility as a general term is described in Section 6.4 and soil sampling methods are described in Section 7.2. Critical values for some physical and chemical properties of upland soils are shown in Section 7.

A ‘fertile’ soil has the following characteristics:

- An adequate supply of the macronutrients nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca) and sulfur (S) and micronutrients, including boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), chlorine (Cl), cobalt (Co) and zinc (Zn), is required to support the production of economic crop yields over the long term.
- Stocks of nutrients are replenished by recycling crop residues, the addition of animal manures, compost, mineral fertilizers, and biological N_2-fixation by legumes.
- Sufficient organic material is returned to the soil through the addition of roots, crop residues and animal manures to sustain soil organic matter, which contributes to proper soil structure as well as nutrient and moisture storage capacity.

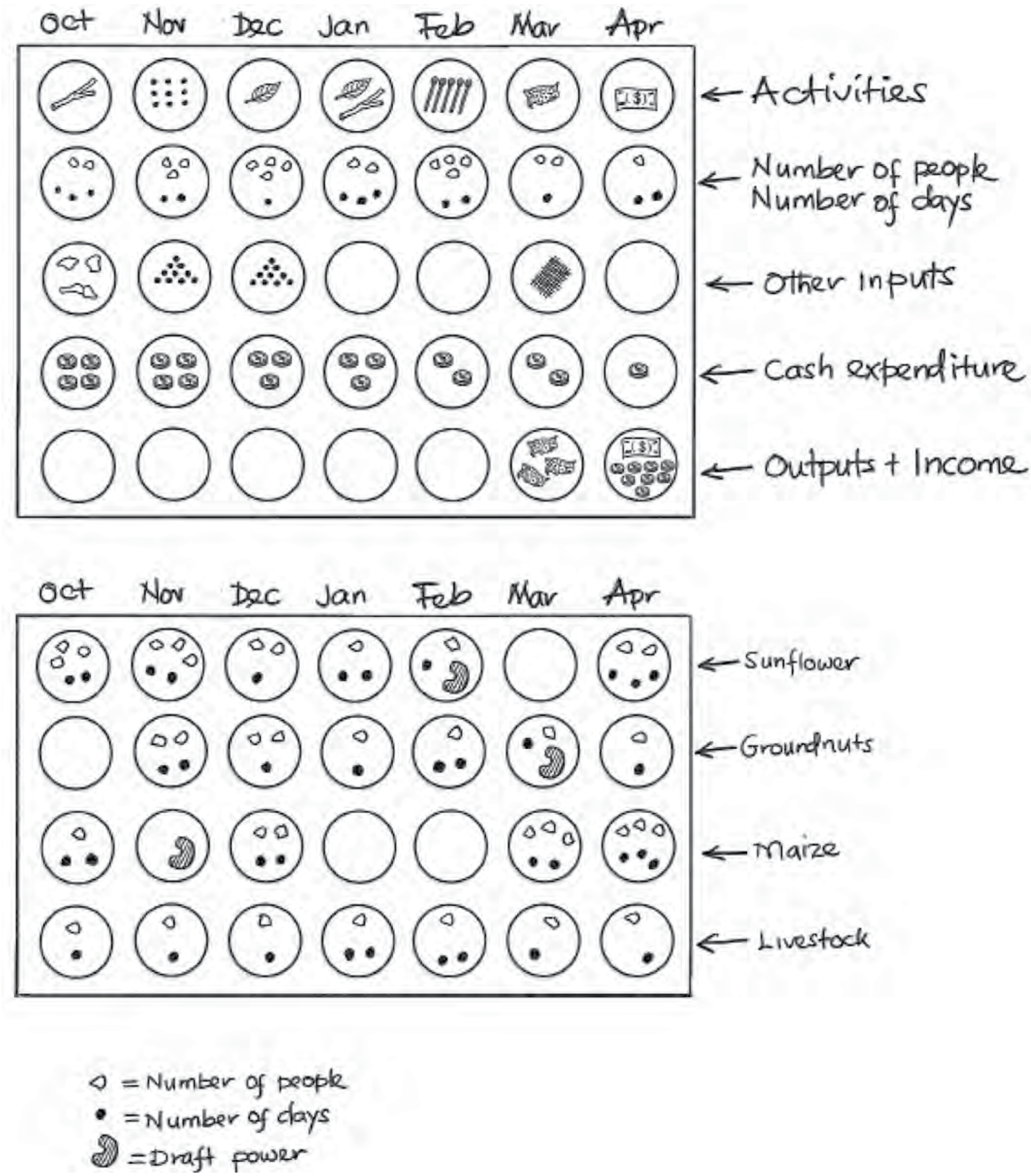


Figure 5.2 Resource budget for labour allocated to different crops.

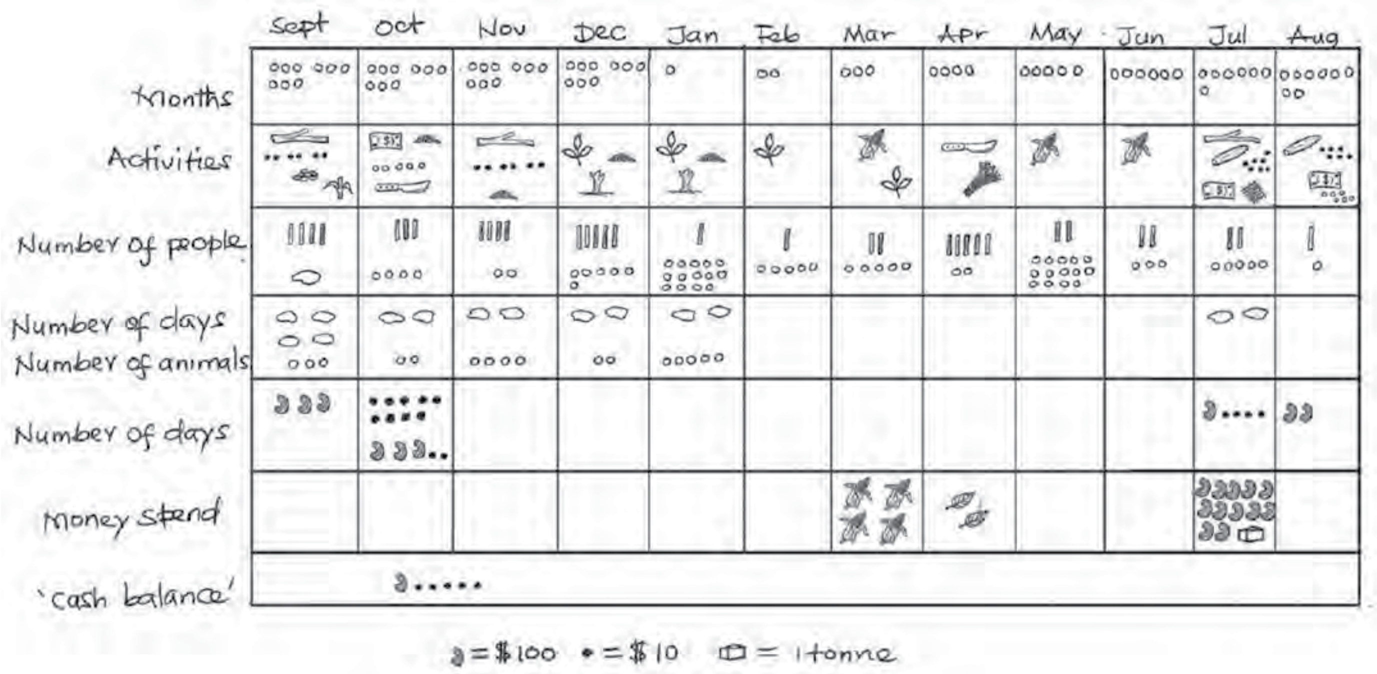


Figure 5.3 Participatory budget constructed by women farmers in Zimbabwe showing the resource outputs and inputs for 1 ha of maize. Symbols and counters were used to construct the budget.

5.4.1 Flows of resources between and within farms

The FSA team should carry out an analysis of the movement of crop products, crop residues and animal manures between fields and farms with particular attention to:

- movement of crop residues between fields (e.g. use of crop residues from in-field on out-field) and farms (e.g. sale of crop residues by farmer without livestock to farmer with livestock);
- movement of animal manures between fields and farms (e.g. sale of animal manure by farmer with livestock to farmer without livestock);
- use of crop products for food security or for sale;
- application of corrective amounts of lime where low soil pH is accompanied by aluminium (Al) toxicity and crops susceptible to Al toxicity are part of the rotation or cropping system;
- sufficient drainage to remove excessive water while retaining sufficient moisture for unimpeded crop growth;
- appropriate soil conservation structures to minimize the loss of soil and nutrients due to erosion and surface runoff water; and
- available P >20 mg/kg, exchangeable K >0.20 cmol/kg.

An *infertile* soil may simply lack sufficient nutrients to sustain crop growth or it may be degraded such that top soil has been lost, the amount of soil organic matter has been depleted, soil structure has collapsed and crops grown on the degraded soil are unresponsive to the application of mineral fertilizers.

It is important to draw a distinction between comparing the fertility of different *soil types* (e.g. light-textured sandy soils versus heavy-textured clay soils) and comparing the *fertility* of soils in different fields and farms with the same soil type. Thus, while soil classification provides useful information on general properties, the soil's current nutrient stocks and *fertility* are a function of recent and past management.

A distinction can also be made between soils that are inherently infertile (i.e. they were infertile prior to being brought into cultivation with small stocks of nutrients or inherent properties unconducive for crop growth) and soils that *were* fertile but have become less fertile following repeated cultivation, often due to poor soil fertility management and lack of soil nutrient replenishment.

Soil fertility usually increases or improves over time when proper ISFM practices are implemented over the medium term (5–10 years).

Farmers typically have three different types of land:

- fertile '*in-fields*' close to the farmer's house which receive organic manure and fertilizer regularly;
- less fertile '*out-fields*' distant from the farmer's house often continuously cropped without nutrient additions; and
- '*bush-fields*' found further away from settlements and more fertile than out-fields because cultivation is less intense.

The important issue is the way differences in soil fertility within farms, between farms, and across farming systems affect agronomic efficiency of fertilizer and manure use and therefore fertilizer recommendations, which lead to important feedbacks in the system.

It is important to assess the productivity of crops grown and the flows of resources (crop residues, livestock feed, animal manures, fertilizer) between each type of land. This will help extension workers identify entry points for agronomic improvement and prioritize those areas within the farm system that should be the subject for improvement.

There are many clues to soil fertility, both direct and indirect, that are evident to the observant visitor. The farmer's and his/her family's welfare (health, nutrition, dress, possessions) provides useful *indirect* clues, as may the size of the farmer's granaries. Farmers who are dependent on agriculture for their livelihood and have achieved a good level of prosperity are likely to be cultivating 'fertile soils'.

5.4.2 Deficiency symptoms

Crop leaf symptoms may provide an indication of acute nutrient deficiencies due to poor soil fertility. Maize (Photo 4.13) and many other crops shows clear leaf deficiency symptoms. Crops are often stunted where there are nutrient deficiencies, particularly of phosphorus (Photo 4.17).

5.4.3 Indicator plants

Some plants, by their presence, are indicative of poor soil fertility or soil fertility problems (e.g. low soil nutrient status, Al toxicity, poor drainage).

5.4.4 Soil sampling

Soil sampling and analysis can provide very useful information on soil fertility provided sampling is carried out properly (Section 7.2). Samples should be taken from the upper 20 cm of soil since this is the zone where most of the feeder roots of crops are found.

When sampling soils in a particular farm, it is important to take account of gradients in soil fertility within *and* between fields. Separate composite samples should be collected from each field within a single farm where there is evidence of soil fertility gradients between fields based on differences in crop growth and appearance and, perhaps, the appearance of the soil itself.

It is also important to investigate the variability of soil fertility among 5–10 farms within a domain and between in-fields, out-fields and bush-fields within individual farms. This will provide useful information when setting ranges for fertilizer recommendations.

Sample soils that have not been cultivated and compare their properties with the cultivated soils sampled. This may help to clarify the extent to which present farmer practices degrade, sustain or even improve soil fertility.

A soil auger should always be used for taking soil samples so that the depth of soil sampled is the same in each sample (Photo 7.3). A representative composite sample should be prepared for each field by mixing together several individual auger samples taken from the same depth and different positions in the respective field.

Soil fertility assessment helps to reveal the potential to increase yields and close yield gaps in a domain. When yields are increased, the need to expand the area under crop production to meet present food requirements is reduced. In this way it may be possible to spare land from agricultural development for other uses.

Sustainable agriculture requires that the soil's ability to produce crops does not decline over the medium to long term. Periodic assessments of soil fertility therefore help to determine whether farmer practices lead to sustainable land management.

Low pH is often considered a constraint to crop production. This is generally only true, however, where crops sensitive to low pH are grown (e.g. cotton) or low pH is associated with Al toxicity and crops sensitive to Al toxicity are included in the cropping system or rotation.

The amount of soil organic matter (SOM) in a soil is usually quite strongly related to the soil's texture or clay content. Soils poor in clay tend to contain less SOM and there is less potential to increase the amount of SOM.

Assessments of changes in SOM over time may provide a misleading picture unless the amount of SOM is corrected for possible changes in soil bulk density.

The clay fraction of highly weathered acid tropical soils is usually dominated by kaolinitic 1:1 clay minerals and Al and Fe oxides. As a result, such soils tend to have a low capacity to store nutrients (i.e. low cation exchange capacity). Soils containing >35% clay dominated by Fe and/or Al oxides may have a strong capacity to adsorb P and therefore reduce the availability of added P for crop uptake.

Soil analysis and data interpretation

The results of soil analysis can provide very misleading information if the laboratory procedures are not carried out correctly. Therefore it is always prudent to submit check samples to verify that a particular laboratory is able to determine consistent values for key soil physical and chemical properties.

Soil texture can be determined in the laboratory (which is usually quite costly) or by using the 'finger test' procedure directly in the field. Soil pH can be determined quite accurately in the field using a portable pH meter (e.g. Pehameter®) (Photo 7.1).

'Critical values' for key soil parameters are rough guides for the need for fertilizer at best. For example, soil total N does not reveal much useful information about N availability to crops in a particular season but analysis of available P and exchangeable K can provide a good indication of whether the soil is able to supply sufficient quantities of these nutrients for crop growth.

5.5 Markets and socio-economic drivers

When identifying suitable domains for promoting ISFM, the focus tends to be on the biophysical factors discussed in terms of, for example, landscape, soil types, climate, and types of crop and livestock systems. Often, little attention is given to socio-economic and policy factors that might influence the ability of farmers in a selected domain to adopt ISFM practices. In this section we discuss the types of socio-economic and policy information that should be included in the farming systems and cropping systems analyses that contribute to the choice of domain.

Information is needed about government investments and policies, market performance and farm-level socio-economic factors that might influence ISFM adoption. This information is not only important for domain selection but will also be useful when selecting particular technical and socio-economic components of an ISFM programme.

5.5.1 Policy environment and the role of governments

Governments can play an important role in promoting ISFM adoption directly through programmes that disseminate information to help ISFM farmers make good production and marketing decisions or through subsidies that make adoption less expensive.

Governments can also assist indirectly through investments in roads, irrigation and research and development. In some situations government can also hinder the expansion of ISFM by keeping in place policies that hinder input/output market development, or by under-investing in public goods such as extension, education, quality control of inputs, and grades and standards for crops marketed.

We will now review some of the government policy issues that should be considered in relation to work on ISFM.

Agricultural subsidies

The FSA team should consider:

- What subsidies are in place or anticipated?
- Who are the target groups?
- What are the crops and zones most likely to be affected?
- Are there any plans for improving output markets where the supply of products is likely to increase as a result of the subsidy?
- Are the targeted people/zones likely to be the same people who will be involved in ISFM programmes? If so, are the subsidies likely to favour or discourage adoption of ISFM practices?
- Are subsidies likely to favour or discourage the development of input and output markets?

When government subsidy programmes are underfunded or the quantities covered by subsidies change from year to year, the uncertainty introduced into the market for private sector retailers can be substantial, reducing their ability to supply ISFM farmers on a timely basis. The FSA team should therefore find out whether subsidies are likely to continue and, if not, what the likely impact on the proposed ISFM programme would be.

ISFM knowledge

The FSA team should consider:

- What role is government playing in supporting the creation (through research) and dissemination (through extension) of ISFM knowledge?
- Are others (e.g. farmer groups, NGOs, input suppliers) also contributing?
- Is there sufficient coordination between government and private sector efforts?
- What does the current level of activity in ISFM knowledge creation/dissemination mean for working with the domains under consideration?

Market information and quality control

The FSA team should consider:

- Do farmers and traders in the zone have access to timely and accurate price information for inputs and outputs? If not, how could information flow be improved?
- Is there a time series of price data available for use by researchers and extension agents who want to analyse changes in the profitability of ISFM practices over time?
- Are farmers satisfied with the quality of inputs marketed or is there a sense that counterfeit or poor-quality products are a major problem?
- Is there a need to improve regulations and or enforcement of existing regulations on quality, grades and standards of agricultural inputs?
- Could poor market information or poor quality control compromise the expansion of an ISFM programme in the domains under consideration? If so, what can be done to improve the situation?

Infrastructure

Road investments are a 'public good' because they make markets work better for both inputs and outputs, as they reduce transportation costs and the problem of farmers not being able to get inputs to their fields and outputs to buyers.

- Is the road network in the domains under consideration so bad that it could seriously constrain ISFM adoption?

Transport costs should be calculated both in terms of dollars per tonne (the cost to the farmer) and dollars per tonne kilometre (a measure of transport efficiency). For example in Table 5.1 the cost of transporting the same quantity of fertilizer to Location 2 is more costly to the farmer ($/t) but less costly in terms of efficiency ($/t km) compared with Location 1. The cost per tonne kilometre may be higher in Location 1 because of poor road conditions.

Evaluating the cost per tonne kilometre of transporting fertilizers to farmers from the nearest wholesaler or the cost per tonne kilometre of shipping crops out at harvest time across the different zones being considered for ISFM interventions can improve the choice of location.

Land tenure policies

Some ISFM programmes may call for substantial investment of labour and capital to restore soil fertility or control erosion. Before selecting domains for this type of programme, it will be necessary to understand the land tenure situation, including both the land tenure laws and the farmers' perceptions of those laws.

- Do farmers believe that the government or the local chief can take their land away from them or do they believe they are the sole owners and entirely in control of the land that they farm, with full rights to sell it or pass it on to their children?
- If farmers do not feel secure about land tenure, how do customary laws and practices introduce land tenure insecurity and how can this be eliminated?

Until these questions are resolved, ISFM programmes and their farmer customers may not want to focus on high-cost, slow-repayment processes for rebuilding soil capital or reducing erosion.

5.5.2 Markets

The key markets of interest for ISFM adoption are for inputs, credit, labour and outputs.

Input markets

An underlying and scientifically proven premise of ISFM in SSA is that the use of inorganic fertilizer and improved germplasm must increase if soil capital is to be maintained and crop productivity is to increase. This means that ISFM adoption could be jeopardized by poorly functioning input and output markets. It is essential that these inputs be available in local markets at the appropriate times and at affordable prices.

Domains with poorly performing or non-existent input markets should not be avoided, but it will be essential for projects and programmes to incorporate market development activities. During the domain decision-making period, a rough inventory and assessment of the input supply sector in the geographic area under consideration should ask the following types of questions:

- Are the retailers located close enough to farmers that transport will not be a constraint ('close enough' will vary depending on roads, types of transport used by farmers to go to market)? This assessment may require some discussion with farmers to see how far they are willing to travel to purchase different types of inputs and what costs are involved. Calculation and comparison of transport cost ($/t) and transport efficiency ($/t km) are useful indicators (Table 5.1).

Table 5.1 Example of a comparison of fertilizer transport costs to two locations.

Parameter	Units	Row	Location 1	Location 2
Amount of material transported	t	a	3.5	3.5
Distance transported	km	b	25	70
Total cost of transport	$	c	30	50
Cost of transport	$/t	c ÷ a	8.6	14.3
	$/t km	c ÷ a ÷ b	0.3	0.2

In some situations, farmers may favour purchasing inputs in more distant markets if the markup for local supply is higher than the cost of the farmer travelling to the more distant location. If existing retailers are not in close proximity, options for addressing the problem include:

  - programmes to help local shopkeepers add inputs to their line of products;
  - providing incentives for more distant suppliers to open a local supply outlet; and
  - working with farmer organizations to consolidate orders from members and organize group purchases to reduce transport and transactions costs.

- Are the retailers experienced and reliable (do they store products properly, can they offer advice to farmers on product use, do they have established relationships with their suppliers that ensure consistent quality and avoid running out of stock, are they constrained by lack of credit, is their pricing system consistent and transparent)?
  This will require visits to a variety of local retailers and interviews with their sales personnel as well as some interviews with their suppliers to be sure that the entire supply chain is 'in good health'. If it is not, stockist training programmes should probably be included as a component of the ISFM programme.
- Are the package sizes sold appropriate for the farmers' ability to purchase?
  Many small farmers prefer to buy fertilizer in small bags containing 20–25 kg instead of the standard bags that contain 50 kg.
- If packaging is not appropriate, what can be done to change the situation?
  In some countries there are laws forbidding retailers from repackaging fertilizers and seeds in an effort to prevent product adulteration. In such cases, manufacturers or major distributors will need to be encouraged to package their products in smaller bags or the programme will need to lobby for changes in the legislation – both approaches take time to realize results.
- Do the types of fertilizer available offer the 'most bang for the buck' (fertilizers with higher nutrient content are generally more expensive per kilogram but less expensive per kilogram of nutrient)? If not, what is the constraint to getting more cost-effective products on the market?
  In some countries, only a limited number of fertilizer compounds are approved for sale, with the national agricultural research institute or a similar body making the regulations. In such cases, the programme will need to work with 'gatekeeper' institutions to evaluate the pros and cons of expanding the list of acceptable products to better accommodate farmers.
- Are improved seeds (certified, open-pollinated variety (OPV), hybrid) available in the zone? If not, why not? Are there regulatory limitations on what is available?
  Some countries continue to ban the use of hybrid seed and many do not allow the use of genetically modified organism (GMO) seed. What types of actions would be needed to encourage retailers to carry improved seed and farmers to purchase it?
- Are ISFM recommendations likely to include the use of pesticides? If so, what pesticides are available on the local market?
- Are there adequate procedures in place to ensure that pesticides are of good quality and retailers are able to inform farmers about their proper use? If not, what can be done to improve the situation?

Credit markets

ISFM recognizes the important role played by mineral fertilizers in building and maintaining soil fertility. If the local cost of ISFM-recommended inputs is beyond the ability of most farmers to purchase on a cash-and-carry basis, however, credit will be important. At this point in the ISFM process, analysts will not have a precise understanding of credit needs because particular components of the ISFM package have not yet been identified. In the absence of more specific information, the analyst may assume that the majority of farmers will require some degree of credit for fertilizer inputs.

In assessing credit availability the FSA team needs to identify the various sources, understand how they have been used in the past, and ask pertinent questions about how they might be adapted to the needs of ISFM farmers.

We will now review four sources of credit that might have relevance to ISFM programmes.

Local shopkeepers or input retailers

If input retailers are also involved in the purchase and trade of agricultural produce (a common situation in some countries), they may be more inclined to offer credit either for inputs or for food purchases during the cropping season (frequently reimbursable in-kind at the harvest). The availability of credit for basic staples can improve the farmer's cash flow situation, enabling some input purchases.

Government credit programmes

Government programmes are often characterized by changing policies and politicization of who has access to credit. Also, there is often a lack of clear sanctions imposed for non-payment, leading to a loss of capital and closure of the credit window. If ISFM adoption is likely to depend on credit in zones where government programmes have not had a good historical record, some efforts may be needed to work with government to improve the programme or to find alternatives.

Micro-finance programmes

Micro-finance is increasingly used for agricultural inputs, but often constrained by the small amounts that can be borrowed and the short periods before loan repayment must be initiated. Interest rates tend to be high (30%), compared with other credit sources (10–15% for government programmes).

Integrated value chain input/output contracts

In an integrated value chain the trader or firm planning to purchase a farmer's output is willing to provide inputs on credit and collect the repayment when the farmer markets the crop. To obtain the input credit, the farmer must sign a contract agreeing to sell a specified amount of production to the trader/firm offering the credit. Such practices are often part of contract farming arrangements.

These tend to be the best option for farmers producing for the market, but are fraught with problems of failure to honour contracts when farmers are not well organized and willing to sanction neighbours who do not adhere to their contracts. The value chain approach is much easier to implement for speciality crops with no alternate local outlets and much more difficult to implement for local staples such as cereals.

To adequately assess credit availability in domains under consideration, the FSA team needs to interview both the credit providers and their clients to get a full picture of how well the systems work and their potential to serve ISFM farmers. Information should be collected on:

- minimum/maximum loan amounts;
- typical time duration of loans;
- interest rates;
- repayment methods (i.e. whether payments are made in cash or in-kind);
- repayment rates; and
- provisions made for rescheduling loans in the case of crop failure.

Crop insurance

Crop insurance programmes may be available locally. Such programmes should be assessed in relation to the incidence of drought and likelihood of delays in the onset of rains. In other words, whether the premiums are worthwhile to the farmer.

Labour markets

Some ISFM practices require increased labour during peak periods and/or the hiring of particular services from those having mechanized equipment for the task (ploughing, threshing). If a farmer has under-utilized family labour and the necessary equipment, this is not a problem. If not, there needs to be a well-functioning market where temporary workers and needed services can be hired or, as in many countries, a system of community work groups that move from farm to farm. Work on a particular participant's farm is carried out in exchange for work carried out by the participant on other group members' farms.

Many ISFM practices require a significant increase in labour during non-peak periods (e.g. composting, collection and application of manure, building anti-erosion structures, special ploughing techniques to improve moisture retention). Promoters of ISFM often assume that an increase in non-peak labour demands poses few problems for farmers. This is often not the case as farmers often engage in alternative income-earning activities (migration, non-farm employment or self-employment activities) during non-peak periods. This means that in assessing the economic incentives for a farmer to adopt a set of ISFM practices, we need to know the opportunity cost of the farmer's labour.

The opportunity cost of additional labour applied to ISFM is the income foregone from some other activity in which the farmer could have engaged during that period of time.

While the opportunity cost will vary from farmer to farmer, a common benchmark for estimating it would be the average wage for a day labourer in agricultural or non-agricultural activities conducted when it is not the peak season.

Output markets

Farmers will need some cash income to pay for the purchased inputs recommended for use with ISFM practices. Unless the farm family has other important sources of income from livestock or non-farm activities, this means producing at least some crops for sale in the market.

In deciding on a domain for the implementation of an ISFM programme and which cropping systems to target, attention needs to be given to how well output markets are functioning. The FSA team needs to consider the following questions:

- Is there strong and growing demand for the crops grown in the target domain?
- What is the current structure of the marketing system (many actors and competitive pricing/few actors and unfavourable prices for farmers/an established role for producer organizations in collecting and consolidating production for forward sales)?
- What is the role of government (direct participation in purchases and sales/regulatory role in terms of grades and standards, import/export tariffs and subsidy or price support policies)?
- Are there well-developed value chains that could serve as a lever for the introduction of ISFM practices into a farming system that already has reliable marketing infrastructure?
- Is there room for making the markets more efficient in a manner that would reduce transaction costs and margins, thereby presenting opportunities to increase producer prices and/or reduce consumer prices?

An analysis of all the information collected on government activities and markets should:

- identify major opportunities and constraints to the adoption and continued use of ISFM practices in the domains under consideration; and
- help the FSA team classify domains in terms of their likelihood to provide a conducive environment for the rapid scaling up of ISFM adoption.

The information will reduce the risk of launching an ISFM programme in an environment that lacks the necessary government services or markets and/or prompt the design of socio-economic components for the ISFM programme that will alleviate the constraints.

5.6 Market development

There is sometimes a tendency to focus on the biophysical components of an ISFM programme while ignoring the potential that small changes in policy or improvements in market efficiency might make to stimulate adoption of the biophysical components. Actions that reduce farm-level fertilizer costs or increase output prices paid to farmers have great potential to stimulate the adoption of ISFM. This is one reason for supporting integrated approaches to ISFM adoption that focus on the biophysical as well as market issues that affect ISFM adoption.

Fertilizer subsidies have been popular with governments as a market intervention to increase fertilizer use and stimulate production growth. Subsidies are also popular with farmers yet there are a number of disadvantages to the use of subsidies:

- They are temporary adjustments that often fail to encourage the structural changes to input markets that are required to change permanently the cost of fertilizer.
- Fertilizer subsidies do not address the issue of output market development.
- Farmers are unlikely to use costly fertilizers if they do not have confidence that they will be able to market enough farm produce to cover the cost of fertilizer.

Where fertilizer subsidies are used, it is essential to incorporate parallel ‘non-subsidy’ interventions to make fertilizer markets more efficient so that subsidies can be reduced as fertilizer prices decrease in response to the non-subsidy interventions.

Non-subsidy government interventions that can reduce fertilizer costs or encourage increased fertilizer use include:

- investments in extension education that show farmers how to increase the efficiency of fertilizer use;
- input market information systems that provide farmers in each locality with periodic (daily, weekly, monthly) information on input and output prices so that farmers make more informed decisions on fertilizer use and produce marketing;
- investments in road, port and storage infrastructure to reduce transportation and storage costs associated with the importation and distribution of fertilizers;
- banking policies that facilitate timely access to foreign exchange so that importers can place orders when market conditions are favourable; and
- effective monitoring of fertilizer quality to identify manufacturers and retailers that supply adulterated or fake fertilizer products.

Activities that are more dependent on private sector initiatives include:

- development of value chains that link input and output markets, often providing input credit and guaranteed output markets for surplus production to farmers (e.g. cotton production systems in West Africa);
- strengthening of farmer organizations so that they can consolidate fertilizer orders for their members and perform some of the procurement and distribution functions themselves; and
- input supplier training programmes that strengthen management skills and encourage the development of distribution networks that link importers, distributors, wholesalers and retailers efficiently in a way that reduces transactions costs.

5.7 *Ex ante* analysis of ISFM technology performance

An *ex ante* analysis is an assessment of the anticipated effects of biophysical components of ISFM (e.g. fertilizer used in combination with hybrid maize seed), based only on information available *before* the programme promoting the component is undertaken (Figure 5.4). In most cases *ex ante* analysis focuses on farm level impacts such as increases in yield, aggregate production and farm incomes. In addition, there are a growing number of decision support tools available to facilitate estimates of impact at a wider scale (region, nation).

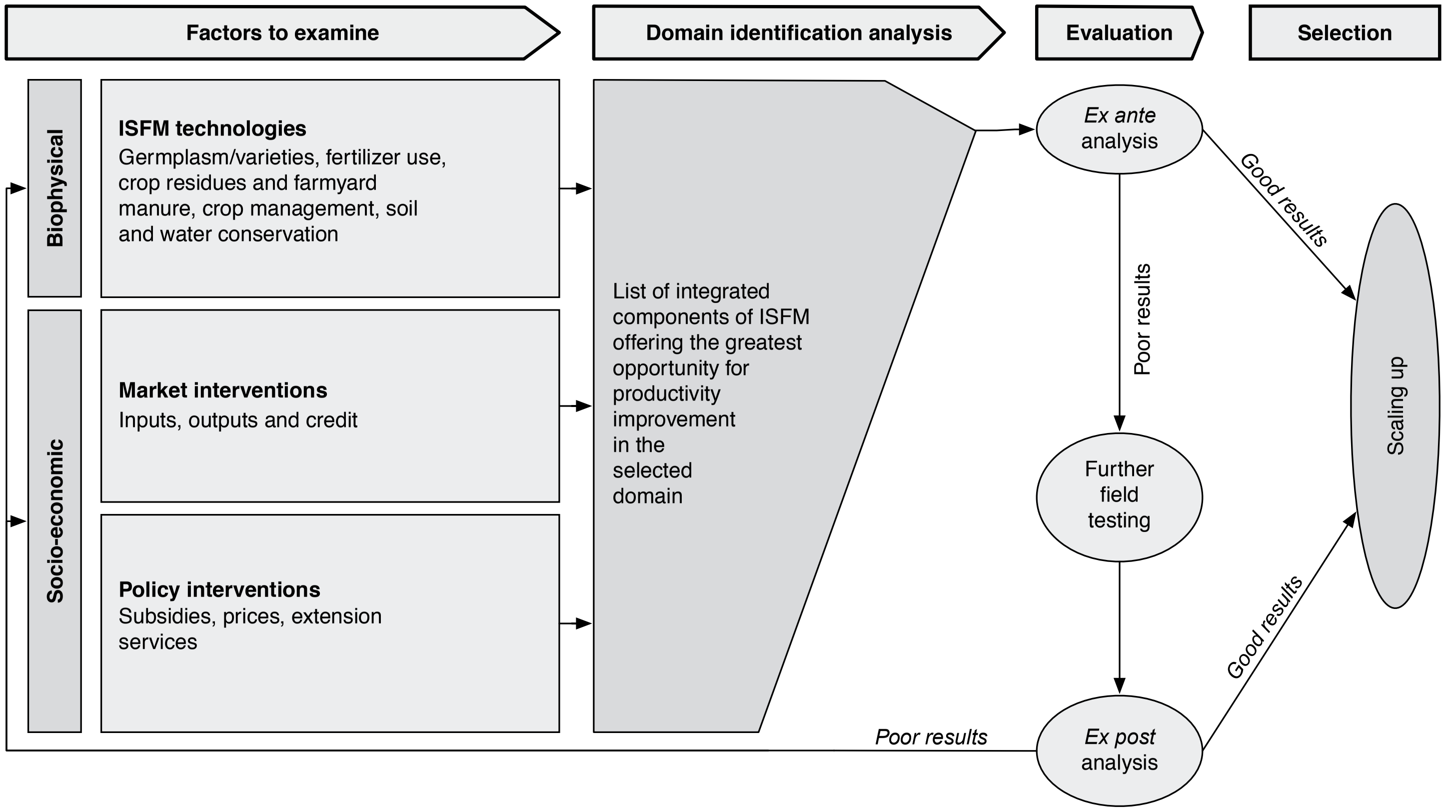


Figure 5.4 ISFM interventions together with related market and policy interventions should be evaluated in the respective domain. Scaling up should only be carried out where *ex ante* or *ex post* analysis shows that the technologies deliver real benefits when implemented in farmers' fields under farmer management.

The objective of conducting an *ex ante* analysis is to:

- verify the extent to which ISFM components under consideration for a particular domain have the potential to improve the three principal objectives of an ISFM programme (i.e. increase crop productivity, improve fertilizer use efficiency and increase farm incomes); and
- identify aspects where more information is required before being able to carry out comprehensive *ex ante* analysis of the ISFM intervention.

There are no hard and fast rules about standards to be met by an *ex ante* analysis, but we suggest some 'rules-of-thumb' for evaluating agronomic efficiency (AE) and economic incentives as well as an indicator to identify situations where market performance may need to be improved.

5.7.1 Agronomic efficiency (AE)

AE can be used for making a rough evaluation of the efficiency of N fertilizer use but provide no information on economic incentives. AE is calculated by dividing the kilograms of additional output attributed to fertilizer application by the kilograms of nutrients applied.

Information on the additional yield attributable to fertilizer generally comes from the analysis of trials conducted on a research station or, preferably, in on-farm trials that include control plots where no fertilizer is applied.

AE ratios for fertilizer used in a given ISFM component should be at or above the levels historically associated with successful adoption of fertilizer in Africa. Typical values for AE based on an extensive analysis of trials carried out in the 1960s and 1970s are shown in Table 5.2.

5.7.2 Economic incentives

The value:cost ratio (VCR) compares the changes in costs and income when a farmer moves from current production practices to a new set of practices. It incorporates both agronomic (yield) and economic (price/cost) information. The VCR is calculated by estimating the value of additional production resulting from a change in practices (i.e. incremental output × market price) divided by the supplementary costs of moving to the new practice (costs of purchased inputs, additional labour use, etc.). If the ISFM practices proposed include costs other than fertilizer (e.g. hybrid seed) these costs should also be included in the denominator.

In SSA, where production risk is significant but difficult to quantify and financial resources are limited, it has been observed that farmers will seldom adopt fertilizer unless the VCR ratio is greater than 2.

Many of these results were based on trials that tested the effect of fertilizer rather than the effect of ISFM practices that integrate fertilizer with other soil fertility management practices. AE for ISFM is usually greater than for fertilizer applied as the sole change in soil fertility management.

Table 5.2 Agronomic efficiency (AE) of N fertilizer for selected crops in SSA.

Crop	Region	AE (kg/kg N)
Maize	Africa	Average 17, maximum 53
Sorghum	East and southern Africa	10
	West Africa	7
Millet	West Africa	7
Cotton		5–6
Groundnuts		9
Coffee	East Africa	8.5
	West Africa	4

The results of a VCR are interpreted as follows:

- When VCR = 1, the farmer breaks even when moving to the new practices. Production may have increased but there is no financial incentive for the farmer to adopt new practices.
- A VCR between 1 and 2 implies that a farmer will earn some profit in making the change. The incentive for change is too small to stimulate adoption.
- A VCR >2 has traditionally been the minimum acceptable VCR for introducing new practices or technologies.

A VCR ratio ≥ 2 provides a buffer offering farmers some protection against risks such as unfavourable weather conditions or pest attacks. In addition, farmers will initially achieve smaller yield responses than those obtained in research and demonstration trails that tend to be the sources of yield response data used to estimate the VCR ratio as part of *ex ante* analysis.

For example, if an application of 150 kg N fertilizer costing \$0.5/kg N produces a yield increase of 3000 kg/ha maize grain with a price of \$0.10/kg, the VCR is calculated as follows:

$$\text{VCR} = 3000 \text{ kg/ha} \times \$0.10/\text{kg} \ / \ 150 \text{ kg N fertilizer} \times \$0.5/\text{kg N}$$

$$\text{VCR} = 300 / 75 = 4.0$$

In this example, the VCR ratio suggests that adoption will lead to large profits even if the yield increase is less than 3000 kg/ha. The threshold VCR ratio value of 2 is reached with a yield increase of 1500 kg maize.

If the value of maize decreases to \$0.04/kg, the value for VCR also decreases to below the threshold VCR ratio value of 2:

$$\text{VCR} = 3000 \text{ kg/ha} \times \$0.04/\text{kg} \ / \ 150 \text{ kg N fertilizer} \times \$0.5/\text{kg N}$$

$$\text{VCR} = 120 / 75 = 1.6$$

To reach the threshold VCR ratio of 2 a yield increase of 3750 kg is required. This is unlikely since it would require an AE value of about 25 kg increased yield/fertilizer N applied.

These calculations serve to underline the importance of carrying out *ex ante* analysis of the VCR ratio to determine whether the anticipated yield increase is likely to result in an economically attractive result.

5.7.3 Market performance

Another indicator that can be used to evaluate market factors is the ratio of fertilizer and output prices (fertilizer/output, F/O), which shows the number of kilograms of output required to pay for a kilogram of fertilizer.

There is no hard and fast threshold value for the F/O ratio because an ISFM component with a very high AE can lead to favourable VCR ratios even when the F/O price ratio appears unfavourable. What is more useful in this case is to compare F/O ratios between different geographical zones (villages, districts, countries). If the F/O price ratio is comparatively high in the domain under consideration, it may be prudent to incorporate some market development activities in addition to narrowly focused activities to inform farmers about improved practices.

Programmes to raise farm-gate output prices or lower fertilizer prices would both contribute to improved F/O ratios. High F/O ratios are a major impediment to fertilizer adoption in SSA. Fertilizer prices generally decrease and output prices increase with improvements in roads, ports, and the removal of tariffs and rent-seeking activities by traders. Such problems can only be resolved with concerted efforts by governments.

Ex ante analysis can be carried out using a simple pocket calculator, but spreadsheet software provides the means to construct simple models that can be used to carry out *ex ante* analysis.

5.7.4 Data required for *ex ante* analysis

A minimum set of data to carry out *ex ante* analysis includes:

- Yield response associated with the particular ISFM practices under consideration; preferably an average yield response based on 5 or more years of on-farm demonstrations, which covered both good and poor rainfall years. It is critically important that the estimated average response include all the fields, including those where there were crop failures or uncontrolled insect attacks.

- Recent past and estimated future output prices for the crops of interest, preferably farmgate prices for the domains under consideration.
- Recent past and estimated future prices for purchased inputs and labour, preferably prices paid by farmers in the domains under consideration. If recent prices have been subsidized, the analyses should also test profitability with unsubsidized prices, to take into account possible discontinuation of the subsidy in the future.

If data are available and analysts have the skills to use spreadsheet tools for estimating simple linear functions, it would also be useful to look at past trends in fertilizer use and how they have responded to price changes. This would require a minimum of 10 years of national data on:

- fertilizer consumption, by crop and type of fertilizer if possible;
- rainfall (frequency and amount); and
- fertilizer and output prices.

In addition, information on changes in soil quality associated with the use of the ISFM components under consideration would provide the analyst with opportunities to incorporate changes in soil capital in the analyses.

There are three key steps to conducting the *ex ante* analysis:

- data collection;
- analysis; and
- deciding on the next steps.

Data collection

Good yield response data are critical to the *ex ante* assessment. Potential sources include national agricultural research institutions, NGOs and extension services that have been managing demonstration plots where accurate records have been maintained of plot size, yields, timing of key activities, input use and other factors affecting yields.

Price data for important crops are often available from national market information systems, but there are also a number of Internet sites that report prices for some products traded in African markets. For example:

- Afrique Verte (http://www.afriqueverte.org/index.cfm?srub=59) has cereal prices going back to 2002 for Mali, Niger, and Burkina Faso.
- FAOSTAT (www.faostat.org) also reports producer prices of major crops each year in local currency, using information sent to them by national governments.

Ideally, weather data are taken from the particular domain under analysis but if data are not available from the domain, weather data can be obtained from national and regional meteorological services.

Input prices are more difficult to obtain. If the government is providing fertilizer subsidies or controlling the fertilizer market, fertilizer prices are usually available from the local office of the Ministry of Agriculture. If prices are entirely determined by market forces, it will be necessary to interview local suppliers to build an historical data series. It will also be important to consider expectations for world market trends in fertilizer prices. This type of information can often be found on commercial Internet sites as well as data series on exchange rates that can influence local prices of imported inputs.

Although much of the data needed for *ex ante* analyses can be obtained from the secondary sources described above, analysts should not exclude the option of collecting information directly from farmers who have used some of the proposed ISFM components in the selected domains. The participatory budget procedures described in Box 5.1 can be expanded to provide more detail on quantities of inputs used, prevailing costs (including any cost of credit) and market prices.

In using the participatory budget approach, the analyst can also collect more qualitative information about how farmers make input use decisions. For example, are they willing to purchase fertilizer if the estimated VCR ratio

Box 5.1 Partial budget analysis for alternative maize production practices

We use the example of a partial budget comparing farmers' current practice with two alternative treatments for maize production (Table 5.3). The steps in the partial budget are as follows:

1. Identify and collect data on the factors that will change (yields, market prices of the output, seed quantities and costs, and fertilizer quantities and costs). If possible enter data into a spreadsheet using formulas to perform the calculations. Because manure use is a constant factor across all three alternatives, we did not need to value it or take into account the labour associated with its use.

2. A possible omission from our simple budget is any additional labour that might be required for weeding due to increased fertilizer use or for harvest and storage due to increased production. If it is known that the alternatives do require more labour, the additional labour should be valued at prevailing agricultural wage rates and included in the budgets to present a more realistic picture of how farmers are likely to view the incentives of the alternative practices.

Table 5.3 Partial budget analysis for alternative maize production practices.

	Current practices		Alternative 1		Alternative 2	
	Local seed + manure		Local seed + manure + fertilizer		Hybrid seed + manure + fertilizer	
Item	kg/ha	Total cost/ value ($)	kg/ha	Total cost/ value ($)	kg/ha	Total cost/ value ($/ha)
Yield	900	270	1500	450	2000	600
Seed	20	8	20	8	20	20
Fertilizer	0	0	50	35	50	35
Costs	–	8	–	43	–	55
Returns		262		407		545
Increase		–		145		138

3. From the data in the partial budget, calculate the AE ratio and VCRs and conduct sensitivity analyses on them (e.g. given prevailing maize prices, what would be the maximum fertilizer price the technology could bear before the VCR fell below a value of 2?).

The illustrative budget results show that:

- Income can be expected to increase by $145/ha if the farmer adds fertilizer at an incremental cost of $35/ha; this corresponds to a VCR of 10.
- If the farmer is already using fertilizer, he/she can increase income by an additional $138/ha by buying hybrid seed at an additional cost of $12/ha.
- The budget analyses show that moving to hybrids is a highly profitable decision (VCR >11).
- Before deciding whether to promote this ISFM component in the selected domain, it will be important to look at the reliability of hybrid seed supply and at farmers' attitudes towards using seed that would need to be purchased annually.

value is < 2? Perhaps they have alternative off-farm uses for their labour and cash that would require an ISFM VCR much higher than 2 before they would switch from off-farm activities to the proposed ISFM activities.

Analysis

In addition to estimating the ratios described above, it is useful to develop partial budgets to compare the costs and returns of alternative ISFM components (Box 5.1). Partial budget analyses are easier to conduct than full-crop or farm budgets because they only compare the costs and benefits of the key budget elements that will change as a result of the proposed interventions. Although a partial budget is a short-cut approach, it is very important that the budgets account for *all* changes in inputs and outputs that occur in moving from one set of practices to another. Otherwise the budget will give misleading results.

Putting the budgets in a spreadsheet provides the analyst with the means to carry out sensitivity analysis on the different yield and cost estimates.

Deciding on next steps

The next steps depend on the outcome of the *ex ante* analysis:

- If the results of *ex ante* analysis shows strong indicator ratios for VCR, F/O and AE, and the partial budget calculations show strong agronomic and economic performance of the selected ISFM components, the next step is to move to preparations for activities to scale up the adoption of the selected components.
- If data were not adequate for conducting the *ex ante* tests or some of the results were weak, a programme of further on-farm testing followed by *ex post* analysis should be devised and implemented. It may be helpful to test some modifications and improvements to the ISFM components.

5.8 On-farm testing of ISFM technologies

ISFM technologies that do not perform well under *ex ante* analysis should be tested further in farmers' fields. The tests should be carried out in several farms selected to represent the variability of on-farm conditions found within the domain. Such work should be carried out in collaboration with national research systems and NGOs with expertise in conducting on-farm tests.

5.9 *Ex post* analysis of ISFM technology performance

Ex post analysis is similar to *ex ante* analysis, except that with *ex post* analysis real data collected during on-farm testing are used in the calculations. Technologies that perform well under *ex post* analysis may be considered for scaling up. *Ex post* analysis may help to reveal key weaknesses of technologies that perform poorly and suggest areas that require further development, refinement and testing.

5.10 Scaling up and scaling out adoption of ISFM solutions

We have now reached the stage where research and development has produced and tested promising technologies that have been proven to be economically advantageous to farmers in the selected domain. Since the domain was carefully identified prior to the adaptation and testing of ISFM practices, target farmers have, of course, already been identified and characterized. The technology may range from a single component of a cropping system (e.g. management of farmyard manure) to several components that are changed simultaneously (e.g. use of improved seed, fertilizer and organic residues).

Reaching large-scale implementation should be the overriding objective of all projects that have successfully introduced ISFM practices. All too often, publicly funded research on ISFM produces interesting results that are only reported in peer-reviewed journals that are not accessible outside the research community. Funding agencies often fail to make the production of extension materials an integral and mandatory requirement of research projects.

In reality, there is never a clear-cut separation between an initial phase of technology development and testing, and a subsequent phase of extension to scale up implementation. Usually there are several iterations between technology testing and extension, building from small- to larger-scale implementation. This makes sense because the technology under development is subject to farmer scrutiny throughout the development phase rather than being developed in a vacuum where only a few farmers are involved.

Unfortunately, in the past, adoption of economically proven technology has often been poor. Some of the reasons include:

- Researchers are not interested or motivated to engage in the extension process.
- Project funding does not include sufficient provision for an extension phase.
- Changes in market conditions (e.g. crop and input prices) make the technology less profitable.
- Changes in emphasis in government policy mean that the technology is either redundant or low priority.

Even with technology proven to provide significant benefits to farmers, it may take 5 years or more to achieve any large-scale adoption and refinements may be required to fine-tune the technology to the often changing needs of the target farmers.

There are two logical steps for reaching scale with implementation:

- scaling up implementation within the domain in which the technology was developed; and
- scaling out implementation to other domains where the technology offered has a good fit.

It is important that projects make provision for an extension phase at project preparation. Either the agency carrying out the research and development plans for an extension phase or the project partners with a government agency or NGO specialized in providing extension.

5.10.1 Development of a communication strategy

A communication strategy should be developed at the outset of activities during domain identification. The project needs to understand and get to know all the actors involved in ISFM in the domain where activities are planned. There may be existing programmes, NGOs and established farmer groups that are working in similar or overlapping areas that can be tapped as a resource.

In addition to the farmers, an array of different target recipients of extension material should be considered:

- **input suppliers** (timing and quantity of fertilizers, seeds and other inputs required; preparation of suitable promotional materials);
- **output markets** (amount and timing of production envisaged, prices);
- **credit providers** (typical loan requirements per farmer and per hectare; preparation of suitable promotional materials);
- **policy makers** (benefits to farmers and the wider community of technology implementation, e.g. expansion of trade, improved food security, increase in production);
- **extension workers** (training in technology implementation; knowledge must be greater and deeper than the farmer); and
- **general public** (improved reliability of food supply; reduced requirement for crop area expansion due to improved crop productivity).

Clearly each actor requires some basic information, but in addition each needs customized information relating to their respective role in the extension programme. The communication strategy therefore identifies the need for a suite of materials. A successful extension campaign will require regular meetings between all the actors involved to review progress and exchange information.

5.11 Development of extension materials

It is important to start thinking about the design of extension materials from the very start of technology development. As workers spend time in the field and get to know their target farmers, it will become clear to whom extension messages should be directed and what kind of materials will be most effective.

For example, in a particular domain, workers may decide that the target audience is young female farmers and that the format should be illustrated posters and leaflets in the local language. Often a whole suite of materials is required, however, that addresses not only the farmers but also other actors who provide services and markets to the target farmers.

Therefore, while leaflets and posters may be sufficient to reach the target farmers, videos and radio broadcasts may be required to inform input and credit suppliers as well as traders. Furthermore, materials may be required to train extension workers. A well-produced 5 min video can help tremendously in explaining the technology and the benefits that accrue from its dissemination to policy makers and the managers of extension teams.

5.11.1 Communicating directly with farmers

Irrespective of the media used to communicate with farmers, the material must include the following information:

- a brief description of the farming and cropping system for which the information on ISFM is relevant;
- gender issues that need to be taken into account;
- benefits to the farmer (e.g. specific improvements to the farmer’s cash income, food security or general livelihood);
- materials and equipment required (quantities of fertilizers, seeds and tools required);
- procedures (a step-by-step guide to technology implementation including timing and frequency of operations, labour requirements);
- simple cost–benefit analysis (details of the additional costs and benefits of the technology and an estimate of the overall quantitative benefit to the farmer); and
- risk (susceptibility of the technology to drought, pests and diseases and market failure).

5.11.2 Extension service providers

Extension advice may be provided by one or several actors:

- **Researchers** should be involved in the initial stage since they depend on feedback from farmers to assess the value of the technologies they develop.
- **Extension workers** may be responsible for providing extension advice but are often poorly funded and motivated and require training to become effective.
- **Input suppliers** benefit from increased sales when farmers have better knowledge and information on input use.
- **Commodity dealers** provide information to their suppliers and will benefit if farmers improve yields and productivity.
- **NGOs, community groups, church groups and schools** may be involved in extension as part of donor-funded projects.
- **Lead farmers** often play an important role in technology transfer.
- **Credit suppliers** may design products to promote particular ISFM technologies.

5.11.3 Types of media

The choice of media is dependent on several factors that should have been reviewed during technology development:

- complexity of the message;
- age and gender of target audience;
- access to communication devices (TV, radio, mobile phones);
- literacy (emphasis on visual versus textual material); and
- language (local, English).

Some or all of the following extension materials may be used in a campaign to promote ISFM:

- **Written materials** can be produced in the format of manuals, leaflets or posters. Leaflets are generally distributed directly to farmers while posters are used to promote technologies in public places, and manuals are usually used to train extension workers.
- **Local radio stations** can be useful to transmit messages to small geographic areas.
- **Mobile phones** are now used widely in SSA. They provide opportunities to circulate simple text messages and farmers can also use them to contact agricultural call centres that provide information on crop management as well as weather and prices of inputs and outputs.
- **TV broadcasts** are usually only suitable for messages transmitted over networks with a large geographical spread.

5.12 Use of information and communication technologies (ICT)

In the past, extension workers relied on a set of standard techniques including 'training and visit', and demonstration plots to disseminate the results of research in farming systems. These techniques relied on a mainly one-way flow of information from research, via the extension worker, to the farmer. More recent work over the past 10 years has shown that good results can also be achieved by a more iterative and collaborative approach between farmers, extension workers and researchers.

Over the past 10 years, with the advent of ICT and the mass adoption of mobile phones, new opportunities for more collaborative extension work are emerging. ICT includes devices such as radio, TV and mobile telephones. The different media formats can be used individually or in combination in a range of approaches:

- **training** farmers to carry out particular tasks and activities;
- **educating** farmers so that they develop expertise and are better able to make decisions and solve problems; and
- **'show and tell'** using visual and oral methods of communication to communicate with illiterate farmers.

The objective is to use the new technologies to:

- take agricultural extension and advisory services to poor farmers living in remote areas with little access to information; and
- give farmers access to information on how to increase yields, reduce losses and make good economic decisions based on up-to-date knowledge of market prices.

5.12.1 Mobile phones

In this approach, agricultural information, contributed by agriculture research organizations and other experts, is reviewed by an expert review board and developed into a database. Leaders in agricultural extension then collect, review and package this information for dissemination using mobile phones.

Farmers access this data by sending queries as short message service (SMS) directly from their phones to a designated number. If a farmer does not have a mobile phone and wants to use this service, he/she can visit the local extension worker equipped with a phone, who will access the data on his/her behalf.

The following information can be made available over mobile phone networks:

- **Market prices.** Daily market prices for produce countrywide gives farmers improved bargaining power when selling or buying.
- **Weather forecasts.** These may include 3 day weather forecasts and seasonal forecasts.
- **Input supplier directory.** This can provide access to input suppliers' phone numbers and addresses countrywide.
- **Google Trader.** This is a virtual marketplace where farmers can post their produce for sale and receive a response giving them contact information of interested traders.
- **Farming best practices.** These are information 'packs' giving detailed farming information on crop agronomy.
- **Fertilizer recommendations.** These can be instantly available by calling a designated number, listening to a pre-recorded voice, and answering questions by pressing numbers on the mobile phone keypad. A text

message reply will appear immediately with specific fertilizer recommendations for the farmer's particular needs. The International Rice Research Institute (IRRI) have pioneered the use of mobile phones where farmers need specific information on nutrient management in rice (http://irri.org/knowledge/tools/nutrient-management-decision-tools).

Use of mobile phones in agriculture extension has been pioneered and developed by the Grameen Foundation (http://www.grameenfoundation.applab.org/ckw/section/index).

Pros

- There is instant access to information and advice.
- There is independence in gaining knowledge (i.e. farmers in remote areas are not as dependent on knowledge passed on during rare visits from extension workers).
- Knowledge of accurate daily market prices empowers farmers to bargain for a better price for their produce.
- Farmers can ask supplementary questions and receive reminders on for example when to apply fertilizer.

Cons

- A service provider must be available for the mobile phone network.
- Farmers need to own a mobile phone or have access to one.
- Extension workers must be equipped with a mobile phone, and be trained in how to use all the relevant applications, so that he/she can pass on information and be a conduit for farmers to access the ICT information database.
- Farmers must have a basic level of literacy.

5.12.2 Computers for Internet access

As for mobile phone use, agricultural information, collated by agriculture research organizations and experts in the field, is reviewed by an expert review board, and developed into a database. Leaders in agricultural extension then review and package this information for dissemination in the form of online computer software with the help of computer experts.

Farmers use computers to access agricultural information from agricultural Internet sites. In some sites, the user answers a set of questions presented in an onscreen form and the computer program returns advice (e.g. fertilizer recommendations). An important issue that must be resolved is the location of a community computer and who should be responsible for maintaining it.

Pros

- The farmer gains access to information and advice.
- There is independence in gaining knowledge.
- There is access to a wide range of agriculture-related Internet sites with photos and short films visible on a large screen (as opposed to mobile-phone screen size).
- One computer per village may be sufficient to serve the entire farming community in the surrounding area.

Cons

- The farmer needs access to a computer with Internet access.
- Farmers must be literate and have a basic understanding of how computers work.
- Extension workers must be trained in using computers and have a knowledge of agricultural sites available and those suitable to the farmers' particular needs.

5.12.3 Video

The advantage of videos presented in the local language is that the material can be understood where literacy levels among farmers are low. Short films made using a simple handheld video recording device can be made by agriculture teachers or scientists from government institutions, NGO experts and progressive farmers to disseminate knowledge to farmers. Films should be made at the grassroots level and contain film footage of activities carried out at the farm that are relevant and instructive to the viewer.

Following the completion of the video, the accuracy, clarity and suitability of the content should be reviewed by agricultural experts before distribution. The content could show:

- a brief verbal overview of the entire process;
- an itemized list of the resources required and associated costs;
- step-by-step instructions on field work required;
- a summary of the costs and benefits; and
- documentation of interactions with farmers in the field that answer common questions and concerns.

Videos can be distributed in the respective village by extension staff and shown in public places, under the extension worker's supervision. Extension staff are crucial to help engage farmers during video screenings, to encourage debate and discussion following the screenings and to provide follow-up support in the field.

A video made in one village may be useful as an extension material in a neighbouring village where the content is relevant, using a rotating distribution system supervised by extension staff. Videos can cover a wide range of agricultural topics, from crop maintenance to livestock management, but relevance to farmer's needs is assured by filming at grassroots level.

Digital Green has pioneered the use of video as an extension tool (http://www.digitalgreen.org/).

Pros

- Literacy is not required because audio is provided in the local language.
- Screenings can be repeated as often as required (i.e. step-by-step approaches to problem solving that need extra reinforcement).
- There is a sense of ownership and relevance when a farmer known to everyone in the village is the lead player on the screen.

Cons

- Every village must be equipped with a video player. Computers with the capability to show videos are less effective as the small screen size limits the size of the audience.
- Extension staff must be trained in the use of video cameras and the basics of film-making.
- The principal beneficiaries of the video will often be the immediate peers of those farmers that are recorded.
- The motivation afforded by a farmer's testimonial may be restricted to the immediate vicinity of the farmer's location.

5.12.4 Data storage

Leading agricultural organizations like the United Nations World Food Programme are constantly looking for ways to learn about the challenges that farmers face in remote areas, and are often handicapped by a lack of efficient and reliable sources of information.

Mobile phones fitted with a GPS device can be used to collect georeferenced data from farms visited. Such data can then be transformed into maps showing spatial patterns of particular issues (e.g. mobile phone ownership) and field problems (e.g. response to fertilizer use).

Mobile phone data may also help to identify geographical locations where services are most needed, and to report their impact. Privacy laws and other legal aspects will need to be considered to avoid misuse of data collected.

ICT will likely have a profound impact on extension services in the coming decades, particularly as the technology becomes more affordable and the capacity of extension workers and researchers to use the technologies increases with training.

5.13 Conclusions

In this section we have reviewed some options for targetting ISFM in cropping systems in SSA. We have emphasized the importance of a proper analysis of farm and cropping systems as well as an assessment of the farmers' operating environment (policy environment and markets) before starting the process of implementation. ISFM interventions should pass *ex ante* analysis before on-farm testing and wider-scale implementation should only proceed when *ex post* analysis shows that the technologies provide economic benefits to farmers.

An important issue is to provide practitioners with relevant extension materials. While this handbook aims to provide extension workers with background information on ISFM, other extension materials on specific cropping systems and farm practices can be provided in a range of formats. Modern technology provides exciting opportunities to reach out to farmers using mobile phones, the Internet and video to complement leaflets and booklets.

5.14 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

Boughton, D., Crawford, E., Krause, M. and de Frahan, B. (1990) Economic Analysis of On-farm Trials: a Review of Approaches and Implications for Research Program Design. Department of Agricultural Economics, Michigan State University, Michigan, Massachusetts. Retrieved August 2012 from http://aec.msu.edu/fs2/inputs/documents/boughton_crawford_etal_SP90-78.pdf.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

CIMMYT (1988) From Agronomic Data to Farmer Recommendstions: an Economics Workbook. CIMMYT, Mexico. Retrieved August 2012 from http://repository.cimmyt.org/xmlui/bitstream/handle/10883/830/13803.pdf?sequence=4.

A standard text on assessing the profitability of agronomic practices, available online.

Crawford, E. and Kamuanga, M. (1987) L'Analyse Economique des Essais Agronomiques pour la Formulation des Recommandations aux Paysans. Department of Agricultural Economics, Michigan State University, Michigan, Massachusetts. Retrieved August 2012 from http://aec.msu.edu/fs2/papers/older/idprp6f.pdf.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

Crawford, E. and Kamuanga, M. (1988) Economic Analysis of Agronomic Trials for the Formulation of Farmer Recommendations. Department of Agricultural Economics, Michigan State University, Michigan, Massachusetts. Retrieved August 2012 from http://www.aec.msu.edu/fs2/papers/older/idprp6.pdf.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

Crawford, E. and Kelly, V. (2001) Evaluating Measures to Improve Agricultural Input Use. Department of Agricultural Economics, Michigan State University, Michigan, Massachusetts. Retrieved August 2012 from http://ageconsearch.umn.edu/bitstream/11686/1/sp01–55.pdf.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

Crawford, E., Jayne, T. and Kelly, V. (2006) Alternative Approaches for Promoting Fertilizer Use in Africa. Agriculture and Rural Development Discussion Paper 22, World Bank, Washington, DC. Retrieved August 2012 from http://siteresources.worldbank.org/INTARD/Resources/ARD_DP22_FINAL.pdf.

A standard text on assessing the profitability of agronomic practices, available online.

Dillon, J. and Hardaker, J. (1977) *Agricultural Decision Analysis*. Iowa State University Press, Ames, Iowa.

Dillon, J. and Hardaker, J. (1993) *Farm Management Research for Small Farmer Development*. Food and Agriculture Organization of the United Nations, Rome.

Two books on the economics of farm management decisions.

Dorward, P., Shepherd, D. and Galpin, M. (2007) Participatory Farm Management Methods for Analysis, Decision Making and Communication. Food and Agriculture Organization of the United Nations, Rome. Retrieved August 2012 from http://www.fao.org/fileadmin/user_upload/ags/publications/participatory_FM.pdf.

A very useful manual on participatory methods.

Galpin, M., Dorward, P. and Shepherd, D. (2000) Participatory Farm Management (PFM) Methods: a Field Manual. Departments of Agriculture and Agricultural Extension and Rural Development, The University of Reading, Reading, UK. Retrieved August 2012 from www.fao.org/fileadmin/.../participatory_FM.pdf.

A very useful manual on participatory methods. Figures 5.2 and 5.3 are presented and discussed in this article.

Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C. and Vanlauwe, B. (2011) Communicating complexity: integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems* 104, 191–203.

A general paper that discusses the NUANCES (Nutrient Use in Animal and Cropping Systems – Efficiencies and Scales) framework for farming systems analysis and evaluation of trade-offs around soil fertility management that leads to the idea of 'best-fit' management practices.

Harrington, L. (1982) Exercises in the Economic Analysis of Agronomic Data. CIMMYT, Mexico. Retrieved August 2012 from http://repository.cimmyt.org/xmlui/bitstream/handle/10883/1005/7030.pdf?sequence=1.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

Kelly, V. (2005) Farmers' Demand For Fertilizer in Sub-Saharan Africa. Department of Agricultural Economics, Michigan State University, Michigan, Massachusetts. Retrieved August 2012 from http://aec.msu.edu/fs2/inputs/documents/WB_demand_paper_August_18_2005_Final_full.pdf.

Kelly, V. (2005) Fertilizer demand in sub-Saharan Africa: realizing the potential. *Policy Synthesis* 77, 1–4. USAID Office of Sustainable Development, Washington, DC. Retrieved August 2012 from http://www.aec.msu.edu/fs2/polsyn/number77.pdf.

Kelly, V. (2006) Factors Affecting Demand for Fertilizer in Sub-Saharan Africa. Agriculture and Rural Development Discussion Paper 23, World Bank, Washington, DC. Retrieved August 2012 from http://siteresources.worldbank.org/INTARD/Resources/ARD_DP23_FINAL.pdf.

Kelly, V. (2007) Guide Méthodologique pour les Études sur les Impacts de la Gestion des Ressources Naturelles. International Resources Group, Washington, DC.

Guide for monitoring and evaluation of project interventions, available online.

Morris, M., Kelly, V., Kopicki, R. and Byerlee, D. (2007) Fertilizer Use in African Agriculture. Lessons Learned and Good Practice Guidelines 144, World Bank, Washington, DC. Retrieved August 2012 from https://openknowledge.worldbank.org/bitstream/handle/10986/6650/390370AFR0Fert101OFFICIAL0USE0ONLY1.pdf?sequence=1.

A series of publications on fertilizer use in sub-Saharan agriculture.

Ojiem, J.O., de Ridder, N., Vanlauwe, B. and Giller, K.E. (2006) Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. *International Journal of Agricultural Sustainability* 4, 79–93.

The concept of socioecological niches can be used to conceptualize how ISFM technologies best fit within smallholder farming systems and is not limited to the role of nitrogen-fixing legumes.

Rufino, M.C., Dury, J., Tittonell, P., van Wijk, M.T., Herrero, M., Zingore, S., Mapfumo, P. and Giller, K.E. (2011) Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems* 104, 175–190.

Sometimes the constraints for ISFM lie at village scale rather than the scale of the individual farm. This paper discusses how manure can best be deployed for ISFM at village scale and demonstrates that there is not enough manure to fertilize all fields, highlighting the need for external nutrient inputs in the form of fertilizer.

Shiferaw, B., Freeman, H. and Swinton, S. (2004) *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. CAB International, Wallingford, UK.

This book discusses the unique features and methodological difficulties of natural resource management impact assessment.

Tefft, J. (1991) Une Analyse Economique des Essais Variétaux et Agronomiques à l'Institut Sénégalais de Recherches Agricoles. USAID and l'Institut Sénégalais de Recherches Agricoles, Washington, DC. Retrieved August 2012 from http://www.aec.msu.edu/fs2/promisam_2/Tefft_Sen_Trials_Report_French_Latest_fu.pdf.

This article provides methods and approaches for the analysis of trial data and the preparation of recommendations.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C. and Giller, K.E. (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya – I. Heterogeneity at region and farm scale. *Agriculture, Ecosystems and Environment* 110, 149–165.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K. and Giller, K.E. (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya – II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. *Agriculture, Ecosystems and Environment* 110, 166–184.

These two articles discuss the diversity of smallholder farmers found in densely populated areas of the East African highlands in relation to soil fertility and approaches to unpacking the diversity through classifying farms.

Tittonel, P., Misiko, M. and Ekise, I. (2008) Talking soil science with farmers. *LEISA Magazine* 24.2, 9–11. LEISA. Retrieved from http://www.agriculturesnetwork.org/magazines/global/living-soils/talking-soil-science-with-farmers/at_download/article_pdf.

Some good ideas on how to discuss ISFM with farmers.

Tittonell, P., van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N. and Giller, K.E. (2009) Beyond resource constraints – exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. *Agricultural Systems* 101, 1–19.

This is a detailed ex ante *analysis of how different approaches for intensification 'fit' for a diverse range of smallholder farmers.*

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R. and Vanlauwe, B. (2010) The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – a typology of smallholder farms. *Agricultural Systems* 103, 83–97.

This article discusses the diversity of smallholder farmers found in densely-populated areas of the East African highlands in relation to soil fertility and approaches to unpacking the diversity through classifying farms.

Photo 5.1 Farmers discussing groundnut response to P fertilizer in Pallisa, Uganda with Peter Ebanyat.

Photo 5.2 Evaluating nutrient management demonstrations with farmers in Western Kenya.

Photo 5.3 Vegetables benefit from the residual effect of fertilizers applied to banana in the highlands of Uganda.

Photo 5.4 A fertilizer store must have a waterproof roof and hard floor. Fertilizers should be stored on wooden pallets to prevent caking.

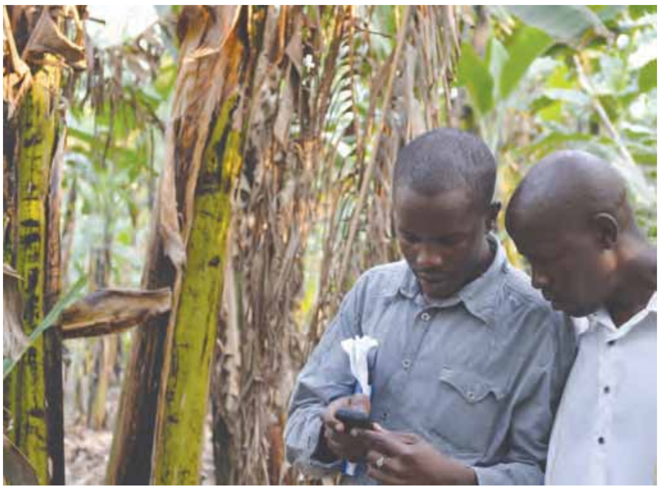


Photo 5.5 Using mobile phones to access crop data in a banana plantation in Uganda.

Photo 5.6 Traders are an essential link between farmers and the market. They should be consulted and involved in campaigns to increase productivity.

Photo 5.7 A computer training centre in Kenya operated by a farm input supplier could become an important tool for disseminating information on farming.

Photo 5.8 Extension campaigns must compete with commercial promotional campaigns for farmers' attention. Mobile phone companies provide an important service in rural areas!

Photo 5.9 A busy input shop in Western Kenya where fertilizers could be purchased using mobile phone credit.

Photo 5.10 Often, the most important contribution that governments can make to ISFM is to improve roads and therefore bring down the farmgate price of fertilizer!

Photo 5.11 A shop owner showing the results from using improved seed varieties for maize.

Photo 5.12 Farmer field days provide opportunities for researchers and extension workers to gather useful feedback from their customers.

Photo 5.13 Workshops where farmers take the lead provide valuable insights into how farmers perceive and judge the results of extension work.

Photo 5.14 An extension worker uses plastic water bottles to demonstrate the principle of 'limiting factors' from Liebig's Law of the Minimum.

Photo 5.15 Much can be learned by visiting input suppliers. For example, which fertilizers are the most popular and how much are farmers buying each season?

Photo 5.16 Farmers at a farmer field school vote with coloured cards to score cassava under normal farmers' practice (1, red cards) and ISFM (2, green cards).

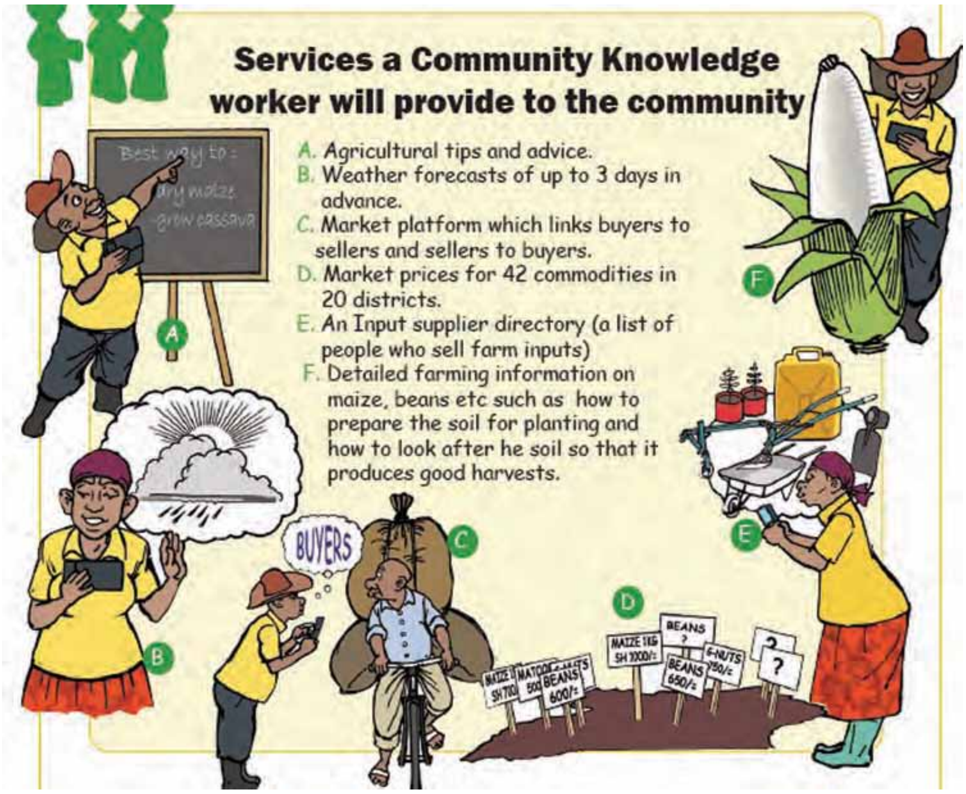


Photo 5.17 The Community Knowledge Worker (CKW) system developed by the Grameen Foundation. CKWs are village people trained to function as extension agents within their own community. Mobile phones are often used to collect georeferenced data and disseminate information.

Photo 5.18 The Nutrient Manager for Rice system developed by the International Rice Research Institute (IRRI) provides an effective means for farmers to obtain fertilizer recommendations for their rice fields over the Internet. The user is led through a series of questions to arrive at a site-specific fertilizer recommendation.

Photo 5.19 Careful preparation of content and process is required in order to prepare effective audio-visual materials for use in extension programmes. The cameraman and sound recordist take instructions from the director who organizes each scene based on prior discussions and planning.

Photo 5.20 Farmers celebrate successful implementation of ISFM in a range of cropping systems in different cropping and farming systems in countries in SSA.

6 Soil and crop production – an introduction

6.1 Introduction

Workers from diverse backgrounds, including those with no technical training in agriculture are involved in both the development and the deployment of techniques to improve farm productivity using integrated soil fertility management (ISFM).

This section is a primer for those involved in promoting integrated soil fertility management but who have little basic knowledge of soils and soil fertility. The aim is to provide information on the principles that underpin the practices contained in ISFM.

6.2 Soil function and quality including quality indicators

The word 'soil' describes the unconsolidated mineral and organic material on the earth's surface that serves as a natural medium for the growth of plants. It is therefore a fundamental attribute that determines primary productivity and life on earth. Soil is inseparable from land, the primary input and factor of production in agriculture.

Human life is dependent on agriculture. The capacity of land to sustain farming activities provides a primary measure of its economic value, and is generally measured on the basis of the ability of soil to perform key functions that sustain crops.

Land is an economic asset that can be traded, exchanged and rented and the value of land is directly related to the fertility of the soils it contains. It is no accident that many of the wealthiest societies have developed in areas where inherent soil fertility is high.

Population density is greatest in African highlands, where soils are generally more fertile and climate allows two cropping seasons. Soil is the farmer's primary asset, and proper soil management will add to the economic value of land over the long run.

6.2.1 Basic soil functions

The soil has five basic functions that are important for sustaining livelihoods:

- **Medium for plant growth.** Soil provides the medium for the production of plant biomass for use as food, feed and fibre. It is this key function that drives the earth's food chain and agriculture.
- **Environmental services.** The soil is responsible for filtering, deactivation or destruction of potential environmental pollutants, controlling flows of rainwater, snow melt and irrigation water including dissolved solutes and suspended sediments. Mineral elements and microbes that occur naturally in soil provide the means for the degradation, buffering and/or detoxification of potentially harmful organic and inorganic products of natural, industrial and anthropogenic (or 'man-made') processes. Soil therefore plays a crucial role in 'cleaning' the air and water that we use.
- **Habitat for diverse biological organisms.** The soil is home to a many micro- and macrofauna and flora, and therefore contributes to maintaining a wide range of genetic or hereditary materials including plants as well as soil flora and fauna.
- **Source of raw materials.** The chemical elements used by growing plants are stored, released, transformed and recycled in soil. The soil also contains minerals and water that can be used as raw materials in economic activities, including agro-industries such as fertilizer manufacturing.
- **Physical space/platform.** Soil provides support for various civil structures such as buildings and roads, and acts as a repository for archaeological treasures as well as a depository for waste materials associated with human habitation.

These basic functions underscore the important role soil plays in agriculture, and the wider environment.

The major focus for sustainable land management concerns the maintenance and enhancement of soil attributes that influence these basic functions and this therefore leads to the concept of soil quality.

6.2.2 Soil fertility

Soil fertility refers to the capacity of a soil to support the production of crops and livestock. A fertile soil can support optimal plant growth from seed germination to plant maturity. The support is mainly the provision of:

- an adequate soil volume for plant root development;
- water and air for root development and growth;
- chemical elements to meet the plant's nutritional requirements; and
- anchorage for the resultant plant structure.

These attributes are often used to describe the overall 'productive quality' of an agricultural soil.

In this regard, we can also distinguish between *inherent* and *dynamic* soil quality indicators:

- *Inherent* soil quality indicators refer to those attributes of soil in its natural state that enable it to function properly and include soil texture, depth and parent material (mineralogy). While soil texture does not change over time, soil depth may be reduced as a result of erosion leading to a change in the texture of top soils. We generally adapt agricultural practices to accommodate inherent soil properties.
- *Dynamic* soil quality indicators concern those attributes dependent on how the soil is managed and include soil organic matter (SOM) content, nutrient- and water-holding capacity, and soil structure. Soil phosphorus (P) and potassium (K) stocks may be increased over time through the application of fertilizers and animal manure. Top soil texture can be regarded as a dynamic property because it is affected by erosion. These indicators change over time and are affected directly by farming practices.

Because it is difficult or even impossible to manipulate *inherent* soil attributes in plant production, the maintenance and improvement of *dynamic* soil parameters is the major focus for soil management in agriculture. For example, there is scope for farmers to manage SOM and associated soil biological properties to influence the productivity of agricultural soils.

6.3 Soil as a source of water and nutrients for crop production

Soils contain four essential constituents:

- **air** (about 20–30% of volume);
- **soil solution** (about 20–30% of volume);
- **mineral fraction** (about 45% of volume);
- **organic matter** (about 5% of volume); and
- **soil fauna and flora**.

In addition to light, crop plants need water and nutrients to grow and develop and produce crop products (i.e. grain, tubers, fruits, dry matter for animal fodder). We will now review the contribution made by soil constituents to crop growth and development.

The porosity of soil (i.e. the volume of the soil occupied by air and the soil solution) provides space for roots and microorganisms to breathe and for water storage. A well-drained soil provides sufficient moisture for plant growth but sufficient aeration for proper root function. In a very dry soil, all pores (small holes and channels between soil particles) are filled with air and root function and plant growth is impaired because of drought stress. In a flooded soil, pores are saturated with water such that the roots of most crops cannot breathe and may therefore die. The exception is rice, which has roots that can breathe in standing water.

Nutrients are present in the soil, the air, or in the water contained in soils (called the ‘soil solution’). There are 18 essential chemical elements that are necessary for normal growth and full development of plants.

These include three essential elements that are necessary for plant growth but not for crop nutrition. Carbon (C) is obtained from carbon dioxide (CO_2) in the air, hydrogen (H) is obtained from water and oxygen (O) from both water and air. These elements, C, H and O, are transformed by photosynthesis, the ‘engine’ of plant growth, into carbohydrates for the growth and development of plants and the production of crop.

Of the other 15 chemical elements we make a distinction between primary nutrients, secondary nutrients and micronutrients based on the amount of each nutrient contained in plants:

- The essential primary nutrients taken up from the soil are nitrogen (N), phosphorus (P) and potassium (K).
- The essential secondary nutrients are calcium (Ca), magnesium (Mg) and sulfur (S).
- The essential micronutrients taken up from the soil are iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), chlorine (Cl), cobalt (Co), molybdenum (Mo) and nickel (Ni).

The soil mineral and organic fractions are major sources for plant nutrients that are released into the soil solution.

6.3.1 Mineral fraction

The mineral fraction in the soil provides support to plant roots and slowly releases nutrients into the soil solution. The mineral fraction is composed of materials differentiated by size (Section 7.4):

- **Sand** has a particle size ranging from 50 to 2000 μm (0.05–2.0 mm) in diameter.
- **Silt** has a particle size ranging from 2 to 50 μm (0.002–0.05 mm) in diameter.
- **Clay** has a particle size <2 μm (<0.002 mm) in diameter.

The proportions of sand, silt and clay determines soil texture (Figures 6.1 and 7.1). For example, a sandy loam soil contains much sand while a silty clay loam contains mainly silt and clay. Soil texture is a very important feature because it determines to a large extent the dynamics of water flow in the soil. Each of the texture classes shown in the diagram has advantages and disadvantages in terms of its use in agriculture.

Soils containing a large proportion of clay (so-called heavy-textured soils) are difficult to work, particularly if the clay fraction comprises so-called shrink–swell clays. Soils containing a large proportion of sand are referred to as light- or coarse-textured soils and are more drought-prone than soils containing more clay. Soil texture can be determined in the laboratory or in the field by rubbing a small amount of wet soil between finger and thumb – the ‘finger test’ (Figure 6.1).

Soil texture affects the behaviour of soils in terms of:

- water-holding capacity;
- nutrient retention and supply;
- drainage; and
- nutrient leaching.

In general, the vertical flow of water in soil (i.e. the water percolation rate) is much higher in sandy soils compared with clayey soils. Nutrients are contained in percolating water and may therefore be transported below the reach of plant roots.

The clay fraction and SOM provide the soil with the means to retain and release nutrients. Clay minerals and SOM have a large surface area relative to their weight and some of the surfaces carry a negative charge, because of substitution of silicon (Si) and aluminium (Al) ions in the clay lattice by cations (positively charged ions) of lower

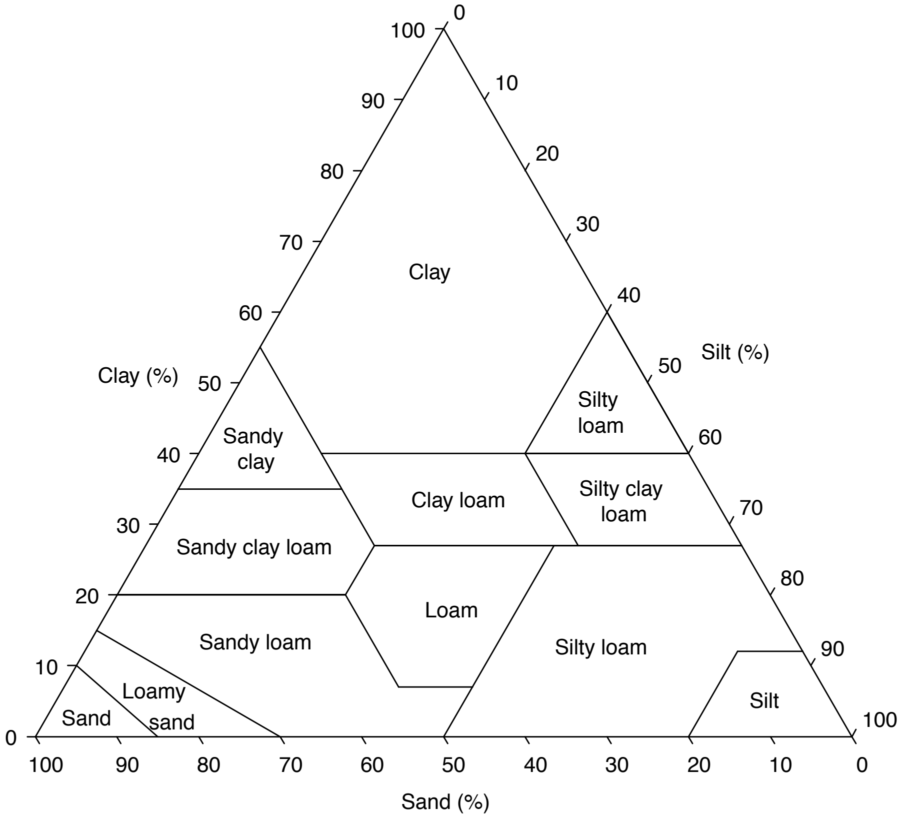


Figure 6.1 Soil texture diagram. Soil texture can be determined in the field using the 'finger test'.

positive charge. They can, therefore, exchange cations (positively charged ions, such as potassium, K^+, and ammonium NH_4^+). This capacity is called cation exchange capacity (CEC) and is expressed in centi-mols per kilogram (cmol (+)/kg) dry soil. In general, the more fertile the soil the higher the CEC.

Under exceptional conditions clay minerals can also retain anions (negatively charged ions), such as nitrate (NO_3^-) on positively charged sites. This capacity is called anion exchange capacity (AEC), also expressed in centi-mols per kilogram (cmol (+)/kg) dry soil.

The size of CEC depends mainly on clay content, the type of clay mineral, the amount of SOM, and the soil pH (i.e. a measure of soil acidity, see below).

The main difference between clay minerals is in their structure:

- 2:1 clay minerals contain two silicate layers for every aluminium oxide or hydroxide layer and have a large CEC capacity (e.g. illite). 2:1 minerals are more common in fertile lowland soils (e.g. rice paddy fields).
- 1:1 clay minerals contain one silicate layer per aluminium oxide/hydroxide layer and have low CEC capacity that is dependent on soil pH (e.g. kaolinite): if the soil is acid, the CEC is small. Most upland soils in SSA contain mainly 1:1 clay minerals that have a low and pH-dependent CEC, and their capacity to retain or supply nutrients to support crop growth is therefore inherently poor.

6.3.2 Organic fraction

The organic fraction in soil or SOM is not homogeneous but rather consists of plant and animal residues in various stages of decomposition, ranging from freshly added crop residues or farmyard manure to soil organic materials that have been modified by biological activity to form humus.

Organic matter contains significant amounts of essential plant nutrients and is an important source of N for plant growth. The N contained in SOM is not immediately available for plant uptake, and is only made available gradually during decomposition. The process of nutrient release involves two steps. First the organic materials undergo **mineralization**, where organic material (crop residues, farmyard manure) is converted into ammonium (NH_4^+) by the action of fungi and bacteria:

$$\text{Organic N} \rightarrow \text{ammonium N } (NH_4^+)$$

In the second step nitrifying bacteria (e.g. *Nitrosomonas* and *Nitrobacter*) convert ammonium into nitrate ions that can be taken up by crop plants in the process called **nitrification**:

$$\text{Ammonium N } (NH_4^+) \rightarrow \text{Nitrite N } (NO_2^-) \rightarrow \text{Nitrate N } (NO_3^-)$$

The major determinants of organic matter decomposition are:

- the quality of the organic materials affected by both the C:N ratio (i.e. the ratio of carbon to nitrogen in organic matter) and the content of lignin and polyphenol compounds;
- soil environmental conditions such as soil structure, soil moisture content, soil temperature, soil pH; and
- the soil's population of micro- and macroflora and fauna (i.e. microbes, nematodes, fungi, bacteria) that are actively involved in the transformations.

Organic materials that contain a small amount of N relative to their C content (e.g. straw) decompose more slowly than materials with a high concentration of N (e.g. legume stover). This is because the amount of N contained in materials with a wide C:N ratio like straw do not provide sufficient N to satisfy the demands of the microbes involved in decomposition. Decomposition is retarded in organic materials that contain a large proportion of lignins and polyphenols (e.g. 'woody' organic materials).

Achieving a tight match (or 'synchrony') between N release from organic matter and crop plant uptake of the released N is an important objective of the management of organic inputs. This is because N released from SOM that is not taken up by crop plants may be leached from the top soil to a depth beyond the reach of crop plant roots.

Organic materials (crop residues, manures) added to the soil also contain other essential plant elements, such as P, Mg, Ca, S and micronutrients which also become available for plant uptake following decomposition. K is not a structural component of organic materials but is contained in the plant cell sap and is therefore released very rapidly when cells rupture at the onset of decomposition. The K content of organic materials can easily be leached out if they are left exposed to rainfall before field application.

In tropical soils, SOM content is an important factor determining the soil's CEC, because of the release of H^+ from functional groups in SOM, depending on the pH of the soil solution. About 55% of SOM is carbon and an increase of 1 g/kg in the amount of soil organic carbon provides an additional 0.4 cmol (+)/kg of CEC (at pH 7).

In addition to supplying nutrients and improving the CEC, SOM provides the following benefits:

- It improves the soil's water-holding capacity, because it can hold up to five times its own weight in water.
- It improves water infiltration into the soil and therefore indirectly improves soil moisture storage and reduces surface water runoff.
- It functions as a buffer for soil pH.
- It binds with Mn and Al, thereby reducing their concentration (and toxicity) in the soil solution.
- It improves soil structure by stimulating activity by soil flora and fauna that produce soil aggregates and therefore indirectly reduces susceptibility to erosion.

Organic materials such as crop residues can also provide a protective mulch cover over the soil, which reduces soil loss by erosion. Organic materials are often not available for use as a mulch, however, because farmers remove them from the field for use as animal feed. Animal manure is then recycled to the field as a source of nutrients.

In most tropical soils, the concentration of organic matter in soil decreases sharply with increasing depth and therefore a small loss of top soil results in the loss of a disproportionately large amount of a soil's SOM.

Due to its many roles, SOM is a key issue in soil fertility management and declining contents of SOM constitute a threat to the sustainability of many agricultural systems. SOM content is related to the soil's clay content because clay particles can protect SOM from decomposition and help to increase the amount of SOM that accumulates in the soil. It is difficult to increase the amount of SOM in coarse-textured soils containing little clay and in soils where the clay's capacity to protect SOM is already saturated. That is why ISFM places more emphasis on the *replenishment* of SOM.

In the context of ISFM, the importance of organic materials is in their potential to improve the agronomic efficiency of fertilizer use.

6.4 Function of nutrients in plant production

A brief description of the function of nutrients in plant growth is provided because visual nutrient deficiency symptoms seen in the field are often related to the function of the respective nutrient in the plant. It is important to remember that all the essential nutrients are required for crop production and lack of a single nutrient will result in poor crop performance even where all other nutrients are available or supplied in sufficient amounts.

A key is helpful to distinguish between nutrient deficiencies and toxicities (Figure 6.2).

6.4.1 Macronutrients

A macronutrient is a nutrient that constitutes at least 0.1% of plant dry matter. The total macronutrient content of a crop may be greater than 4% of total plant dry matter.

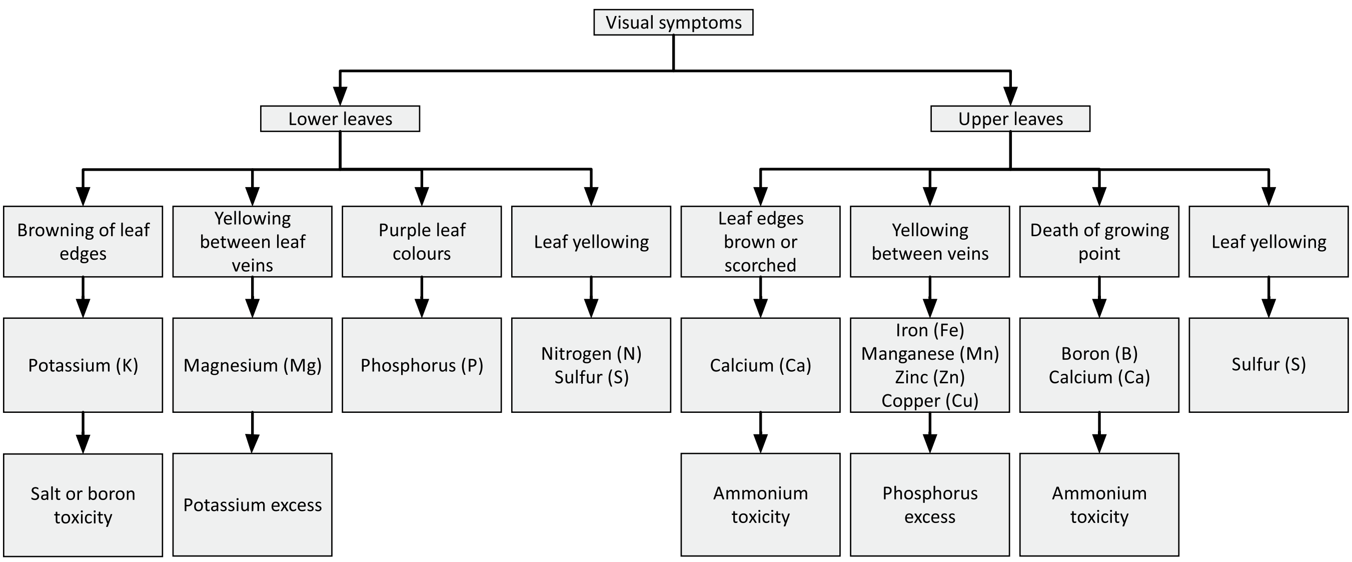


Figure 6.2 Visual symptoms of nutrient deficiencies and disorders. Symptoms can be caused by other factors (e.g. drought can also cause browning of leaf edges). Purpling may also be seen in some cereal varieties that are rich in anthocyanins. Phosphorus deficiency is often indicated by stunting (e.g. in maize) and small leaf size (e.g. in legume crops).

Nitrogen (N)

N is combined with C, H and O to form amino acids, the building blocks of proteins and enzymes. It is also part of the chlorophyll molecule and several vitamins. N is required for plant dry matter production and the production of proteins in grain crops. N-deficient plants are stunted, and older leaves of N-deficient plants turn pale green to yellow starting at the leaf tip because N is translocated to younger tissue. N-deficient crops reach maturity prematurely resulting in reduced yield. Protein content is reduced in N-deficient grain crops. N is taken up by plants in the form of nitrate (NO_3^-) and ammonium (NH_4^+) ions.

Phosphorus (P)

P plays a major role in energy storage, is a component of DNA and is required for cell membrane maintenance. P is required in large amounts where plant growth takes place (i.e. in shoot and root tips). P is important for root and flower development and seed and fruit production. P contributes to plant disease resistance and crop quality. P is readily translocated from older tissue to younger tissue, causing symptoms of dark to blue-green coloration to appear on older leaves of some plants. Under severe deficiency, purpling of leaves and stems may appear. As plants mature, most of the plant P is transported into seeds and fruits. When P is deficient, root development and tillering is poor, plant growth is retarded, plants appear stunted, crop maturity is delayed and flowering and fruiting are poor. P is taken up from the soil solution in the form of $H_2PO_4^-$ and HPO_4^{2-} ions.

Potassium (K)

K is contained in the cell sap and catalyses the activity of many enzymes involved in plant metabolism. K also regulates electrical charge where energy transfer takes place and therefore affects protein synthesis. Plant water use is controlled by the effect of varying K concentration on leaf stomata openings. K also promotes the translocation of sugars for plant growth or storage in grains and tubers. K is required for atmospheric N_2-fixation in leguminous plants. K is also important for crop quality (e.g. grain size) and disease resistance. Plants deficient in K show chlorosis along leaf edges (leaf margin scorch) of older leaves from which K has been translocated to younger tissue. K-deficient plants are stunted and are often more prone to lodging and more susceptible to drought. K is taken up by plants as the ion K^+.

Sulfur (S)

S is a constituent of amino acids and therefore essential for protein formation. S is required for the synthesis of chlorophyll and some vitamins, as well as for biological N_2-fixation in legumes. Younger leaves of deficient plants turn pale yellow, growth rate is reduced and maturity is delayed. Plants take up S from the soil as SO_4^{2-} ions.

Magnesium (Mg)

Mg is a constituent of chlorophyll and therefore essential for photosynthesis. Mg activates enzymes and is required for carbohydrate transport. Mg is mobile in plants and deficiency symptoms appear as inter-veinal chlorosis in older leaves. Inter-veinal tissue turns orange-yellow in some crop plants (e.g. potato, soybean). Mg is taken up by plants in its ionic form of Mg^{2+} ions.

Calcium (Ca)

Ca is involved in cell membrane formation and activates enzymes involved in protein synthesis and carbohydrate transfer and neutralizes potentially toxic organic acids, sulfates and phosphates. Ca is essential for seed production in calcium-demanding plants (termed 'calcicole' plants) such as groundnuts. Ca influences water movement, cell growth and division and is required for the uptake of N and other minerals. Ca affects plant growth indirectly when soils are limed with $CaCO_3$. Because Ca is not mobile in plants, deficiency symptoms occur on younger leaves and leaf and root tips. Symptoms associated with Ca deficiency include stunting of new growth in stems, flowers and roots, and curled or cupped leaves with black spots and yellow leaf margins. Ca is taken up by plants in the form of Ca^{2+} ions.

6.4.2 Micronutrients

A micronutrient is a nutrient that constitutes less than 0.1% of plant dry matter. Micronutrient deficiencies may result in poor responses to the macronutrients N, P and K. Deficiencies occur where soils are inherently poor in micronutrients or where soils have been degraded. Micronutrient deficiencies are often related to soil pH.

Iron (Fe)

Fe is important for the synthesis of chlorophyll. Plants deficient in Fe may exhibit pale leaves and inter-veinal chlorosis (yellowing) of the whole leaves. Fe is taken up by plants as Fe^{2+} and Fe^{3+} ions.

Manganese (Mn)

Mn is essential for some enzyme activity. When deficient, the symptoms are similar to Fe deficiency, with pale young leaves and green veins. Sometimes brown, black or grey spots are observed next to leaf veins. Mn is taken up by plants as Mn^{2+} or Mn^{3+} ions.

Boron (B)

B is required for nucleic acid synthesis, pollen germination and the growth of the pollen tube. B promotes root development, enzyme activity and is associated with lignin synthesis, sugar transport, seed and cell wall formation, calcium uptake and proper water relations. B-deficient plants show curled, brittle leaves and discolored or cracked fruits, tubers and roots. Leaf symptoms are usually found on leaf tips. B is taken up by plants from the soil or absorbed by leaves as $(BO_3)^{3-}$ ions.

Zinc (Zn)

Zn plays a role in the regulation of plant growth and the transformation of carbohydrates and is required for nucleic acid synthesis and enzyme activation. Plants deficient in Zn show inter-veinal chlorosis at the base of young leaves (by contrast with Fe deficiency, where the inter-veinal chlorosis occurs along the whole leaf). Zn is taken up by plants as Zn^{2+} ions.

Copper (Cu)

Cu is an essential part of the enzyme system that utilizes carbohydrates and proteins and is important for reproductive growth. Cu-deficient plants may show die-back of shoot tips and old leaves develop brown spots. Cu is taken up by plants as Cu^{2+} ions.

Molybdenum (Mo)

Mo is required for protein synthesis and N uptake and is required by N_2-fixing bacteria in legumes. Plants deficient in Mo have pale leaves with rolled margins and seeds may not form. Plants affected by Mo deficiency may also show symptoms similar to N deficiency. Mo is taken up by plants as Mo_4^{2+} ions.

Chlorine (Cl)

Cl is involved in the movement of water and solutes in plants and is important for nutrient uptake. It also plays a role in photosynthesis. When deficient, plants show wilting of young leaves, stubby roots and yellowing of leaves. Deficiency seldom occurs because Cl is found in the atmosphere and in rainwater. Cl is taken up by plants as Cl^- ions.

Cobalt (Co)

Co is required by N_2-fixing bacteria and extreme deficiency may cause legumes to exhibit symptoms similar to N deficiency. Co is taken up by plants as Co^{2+} ions.

Nickel (Ni)

Ni is required for the enzyme urease which breaks urea down into forms of N that can be taken up by plants, and for Fe absorption. Ni is taken up by plants as Ni^{2+} ions.

Sodium (Na)

Na is important for the regulation of water movement and balance of minerals in plants. Na is taken up by plants as Na^{+} ions.

Silicon (Si)

Si is a major component of cell walls and helps to protect plants from piercing by sucking insects. It enhances leaf presentation, improves heat and drought tolerance, and reduces transpiration. Deficiency symptoms include wilting, poor fruit and flower set and increased susceptibility to insects and disease attack. Si is taken up by plants as $(SiO_4)^{4-}$.

6.5 Definition of soil fertility

We can define soil fertility as:

The capacity of soil to supply sufficient quantities and proportions of essential chemical elements (nutrients) and water required for optimal growth of specified plants as governed by the soil's chemical, physical and biological attributes.

To achieve farmers' production objectives, more nutrients are usually required than can be supplied by the soil. For example, a soil considered 'fertile' in its natural state may be able to sustain maize grain yields of just over 2 t/ha. It will be necessary, however, for the farmer to raise the fertility of the field by adding nutrients in the form of crop residues, fertilizer or both to reach a yield of 5 t/ha. This demonstrates that soil fertility is a *relative* rather than *absolute* term. It is important to consider whether a particular soil will respond to the use of inputs to improve soil fertility and increase yields. It is this responsiveness to management that often constitutes a major criterion used by farmers for a 'fertile' soil. Farmers may only become aware of the potential to *improve* the fertility of their soils when the effect of using improved germplasm combined with better crop residue management and the addition of mineral fertilizers has been demonstrated in their own fields!

For crop production purposes, soil fertility should therefore be viewed in the broader context of soil productivity, putting into perspective the soil's chemical, physical and biological properties as they regulate nutrient and water supply and provide the other environmental conditions required for plant development.

Most farms in SSA contain a mixture of fertile, infertile and degraded soils. The variability of soil fertility within a particular farm has generally not received sufficient emphasis in the past but is a key feature of ISFM.

6.6 Measurement of soil fertility

Researchers, extension workers and farmers use different methods to assess soil fertility. Researchers and extension workers use soil tests performed on samples taken from a particular field or part of a field to estimate the fertility of soils (Section 7.2). Soil tests are reported in standard units (Table 7.8) and can be interpreted in relation to critical values (Table 7.9). Soil sampling and testing is only useful where:

- soil samples have been collected after taking into account the variability of soil fertility between different parts of the farm evident from field inspection;
- a reliable laboratory is used to analyse the samples; and
- cross-check and standard samples are used to verify that the analytical work in the laboratory has been carried out correctly.

Farmers generally use several indicators to assess a soil's potential productivity, including:

- the dominant vegetation as an indirect indicator of soil fertility;
- the presence of specific soil fauna;
- the colour as an indicator of organic matter content;
- the soil's nutrient-supplying capacity (i.e. fertility) based on the appearance of crops from planting to maturity;
- crop yields, based on previous harvests over several seasons;
- the soil's capacity to supply water to crops based on the appearance of crops during periods of drought; and
- the soil's structure and workability, based on the ease or difficulty involved in cultivating the soil during land preparation.

6.7 Conclusions

Soil comprises mineral and organic constituents combined by biological activity by soil micro- and macroflora and fauna to produce the medium for crop growth. Some attributes, like soil texture, are more or less fixed while other attributes like the soil's capacity to store and release nutrients are strongly influenced by the farmer's management practices. All crops require an adequate supply of mineral nutrients, whether supplied by the soil's store of nutrients or through supplements supplied in the form of organic inputs and mineral fertilizers.

An explanation of the importance of ISFM and how it can contribute to agricultural development and economic improvement is the subject of the previous sections in this handbook.

6.8 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

There are a large number of basic texts in soil science that will provide useful background reading.

Gregory, P.J. and Nortcliff, S. (eds) (2012) *Soil Conditions and Plant Growth*. Wiley/Blackwell, Oxford.

An excellent reference text.

Marschner, H. (1995) *Mineral Nutrition of Higher Plants*. Academic Press, London.

Mengel, K. and Kirkby, E.A. (2001) *Principles of Plant Nutrition*. Springer, Dordrecht.

Two standard reference texts on plant nutrition.

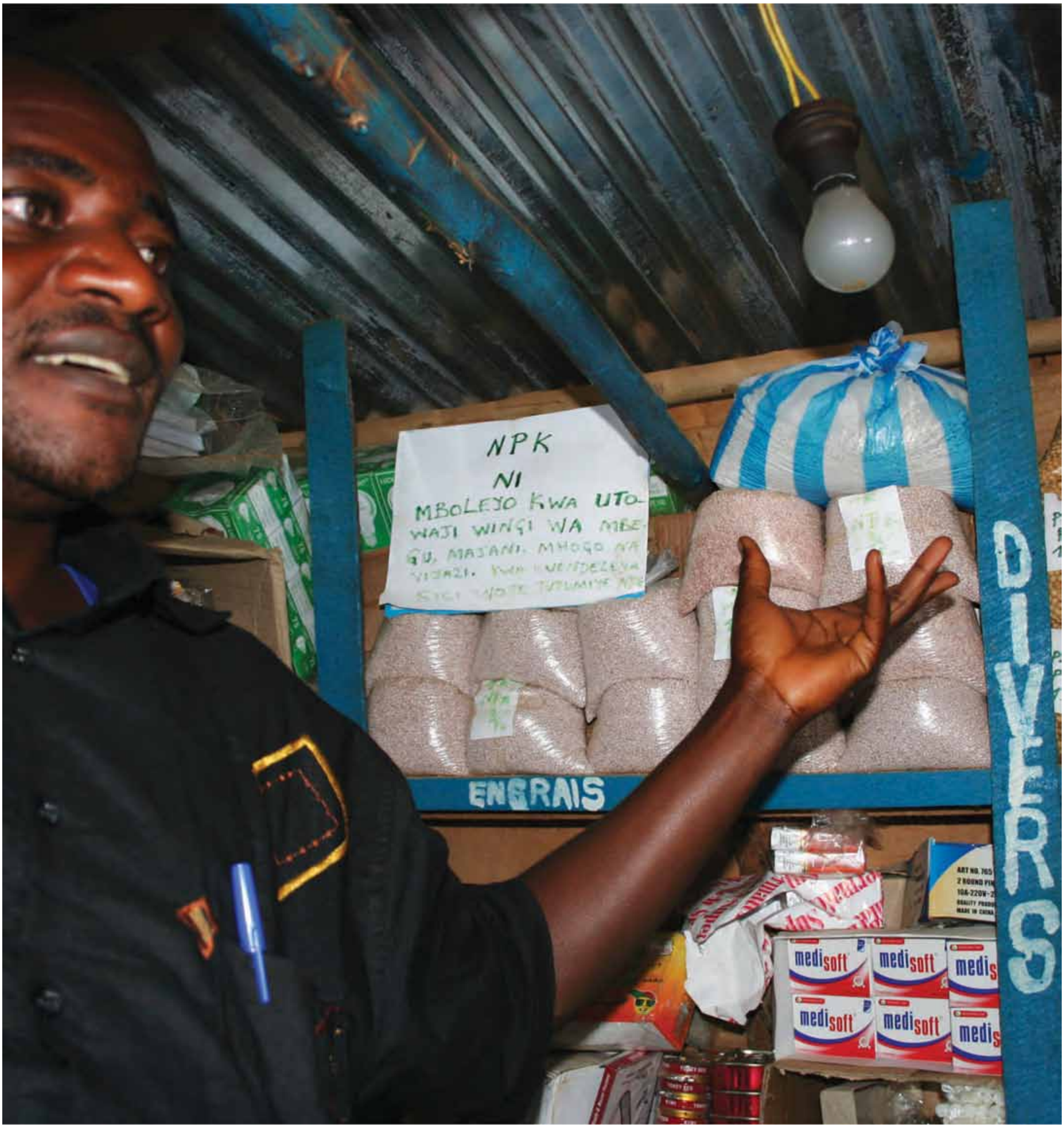
Photo 6.1 Ideally, soil pits should be dug to allow a thorough examination of the soil profile. The soil profile is also revealed in drain sides and road cuts.

Photo 6.2 Soil samples should be taken with a soil auger using a proper sampling pattern.

Photo 6.3 Soil texture is costly to determine in the laboratory. Texture can also be determined using the 'finger test'.

Photo 6.4 The Edelman auger is designed to sample equal amounts of soil from each depth sampled.

7 Tables and reference information



7.1 Introduction

In this section reference tables are provided on:

- soil sampling;
- farming systems analysis;
- soil fertility management;
- crop nutrition;
- fertilizer use;
- farm economics; and
- general information.

7.2 Soil sampling

The purpose of soil sampling is to provide material for soil testing. A representative soil sample is a prerequisite for successful soil testing. A layer of soil 20 cm deep weighs 2000–3000 t/ha. A composite sample of about 0.5 kg is taken from a field, which may represent <1 ha or ≥30 ha.

In the laboratory, about one teaspoon of soil (a few grams) is taken from the 0.5 kg sample for use in the analytical procedure (Figure 7.1). Soils are normally heterogenous and wide variability can occur even in fields that are apparently uniform. Unless the field sampling procedure is implemented properly, there is a real chance that the soil analytical data will not be representative of the field. The procedure involved in collecting a representative sample can be summarized as follows:

- Check the area to be sampled for notable features (e.g. slope, soil types, vegetation, drainage).
- Draw a sketch map, and identify and mark the location of sampling points.
- Avoid sampling across different soil types and land uses and in distinctive spots (e.g. ash and manure piles, threshing places, wet spots).
- Take a composite sample (25–30 individual sub-sample cores) from a circular area, of about 10–20 m diameter before moving to another area to be sampled.
- Each sub-sample must be taken to the full sampling depth (i.e. 0–20 cm or 20–40 cm).
- Each composite sample should be clearly identified and matched with the sketch map or field location (use a GPS device to speed up this process and improve accuracy).
- Mix composite samples thoroughly and if necessary, reduce sample weight by subdividing (e.g. quartering).
- Avoid any contamination of samples by other soils, sampling tools, sampling bags, fertilizers, etc.

A field should be tested once every 3 years and samples should be taken just prior to seeding or planting but before fertilizer application. In perennial cropping systems samples should be taken at the same time of year.

The main objectives of soil testing are as follows:

- to help identify the reasons for poor plant performance (diagnostic tool);
- to provide an index of nutrient availability or supply in a given soil;
- to predict the response to soil amendments (e.g. lime) and fertilizer;
- to provide a basis for recommendations on the amount of plant nutrients to apply;
- to assist in preparing nutrient budgets on a per-field or per-farm basis; and
- to evaluate the fertility status of a larger soilscape.

A soil test is a chemical method for estimating the nutrient-supplying power of a soil. Although plant analyses are extremely valuable in diagnosing nutrient stress, analysis of the soil is essential for determining the supplemental nutrient requirements of a particular crop.

Compared to plant analysis, the primary advantage of soil testing is its ability to determine the nutrient status of the soil before the crop is planted. However, soil tests are not able to predict the quantity of a nutrient taken up by a crop. To predict the nutrient needs of crops, soil test results must be calibrated against nutrient uptake and yield in field trials.

The following equipment is useful for field appraisal of soil fertility:

- portable pH meter (e.g. Pehameter®, FieldScout SoilStik® pH meter, Kelway® Soil pH and moisture meter);
- Edelman soil auger;
- soil texture key (e.g. United States Department of Agriculture (USDA) Soil Texturing Field Flow Chart); and
- sample bags and labels.

Source: Dierolf, T.S., Fairhurst, T.H. and Mutert, E.W. (2001) *Soil Fertility Kit: a Toolkit for Acid, Upland Soil Fertility Management in Southeast Asia*. Potash & Phosphate Institute (PPI), ProRLK, GTZ GmbH, Singapore.

7.3 How to determine soil bulk density

Bulk density is the weight of soil for a given volume. It is used to measure compaction and to correct measurements of soil organic matter for differences in bulk density. In general, the greater the density, the less pore space for water movement, root growth and penetration, and seedling germination.

Bulk density measurements should be performed at the soil surface and/or in a compacted zone (e.g. plough pan) if one is present. Several samples should be taken to get a representative bulk density measurement of the area.

A cylindrical metal or plastic coring tool of known volume is driven into the soil to a desired depth. The intact core is removed, dried in an oven at 105°C, and weighed.

$$\text{Soil bulk density } (\text{mg}/\text{m}^3) = \frac{\text{Oven-dry weight of soil}}{\text{Volume of soil}}$$

7.4 How to determine soil texture in the field

The soil mineral fraction is divided into three fractions depending on particle size:

- **Sand** has a particle size ranging from 50 to 2000 μm (0.05–2.0 mm) in diameter. Sand imparts a gritty feel to soil due to the shape of the individual particles.
- **Silt** has a particle size ranging from 2 to 50 μm (0.002–0.05 mm) in diameter. When moist, silt has a floury feel and does not ribbon when pressed between the thumb and forefinger due to the shape of the individual particles. When placed between the teeth silt has a gritty feeling.
- **Clay** has a particle size <2 μm (<0.002 mm) in diameter. Clay exhibits colloidal properties, has a negative charge and is flat and plate-like in shape. Moist clay is sticky and will ribbon readily when pressed between the thumb and forefinger. When placed between the teeth clay has a smooth slick feeling.

Soil texture is estimated from the feel of moist (but not wet or dry) soil using a key that distinguishes between the main texture classes (Figure 7.1). Take a small amount of freshly dug soil. Add water and knead the soil until the soil crumb structure has broken down. Use the key to identify the appropriate texture class (Figure 7.1).

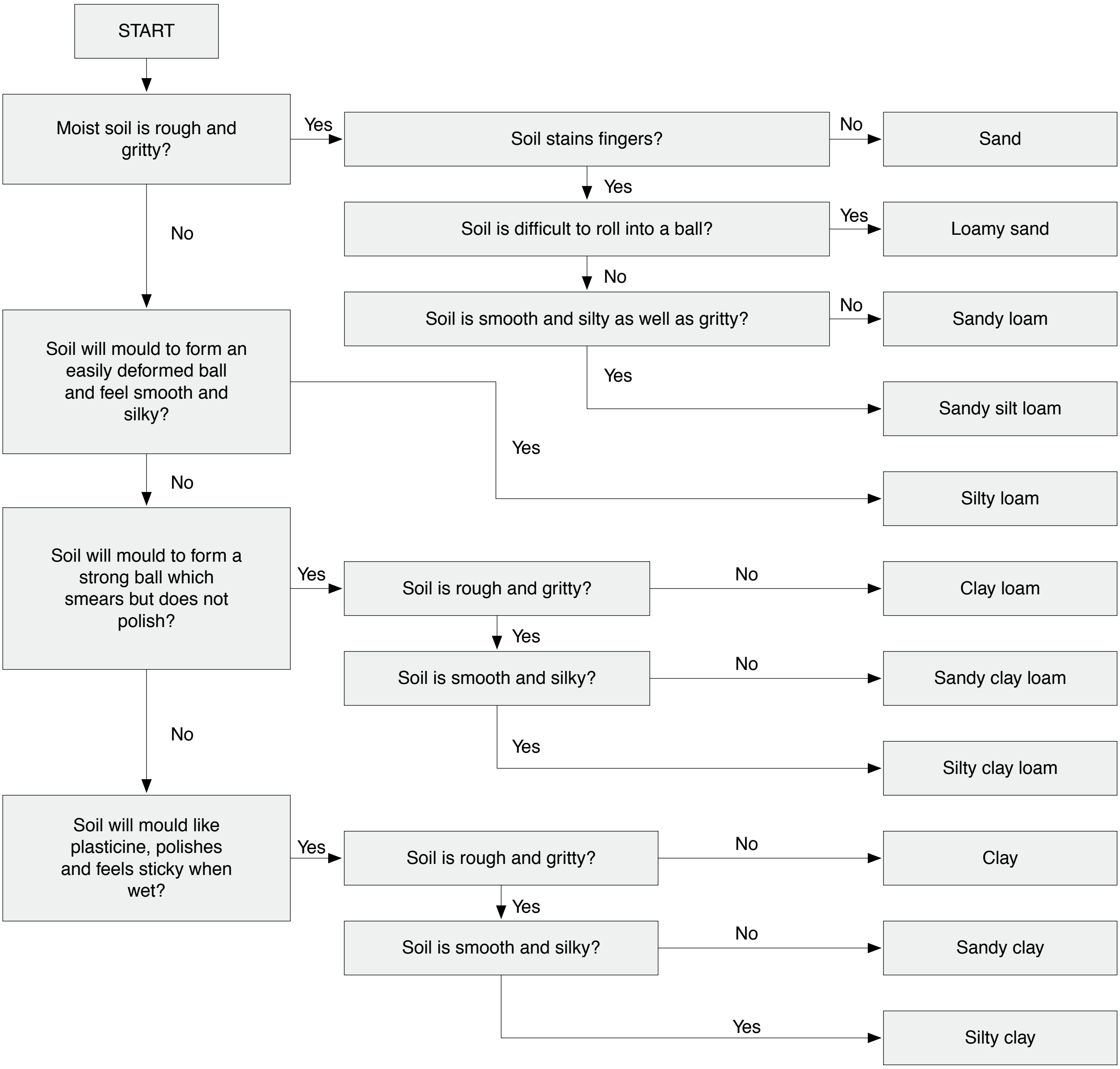


Figure 7.1 Key to distinguish between the main soil texture classes based on the 'finger test'.

7.5 Farming systems analysis

Table 7.1 Improvement in ISFM is a process involving three key steps.

Activity	Purpose
Diagnose major soil fertility problems and identify how soil fertility management can be improved	
Household and gender analysis: tasks and control.	Determine who does what so that the appropriate family members are involved.
Map for nutrient flows on the farm.	Develop an overall understanding of the farming system and nutrient flows within it.
Household soil fertility management.	Learn about the farmer's knowledge and practices.
Cropping/fertility history.	Determine the possible effects of past management on soil fertility.
Nutrient deficiency symptoms.	Identify critical soil fertility problems that need to be corrected.
Evaluate soil fertility practices.	Learn about current practices that could be improved.
Diagnosis.	Determine possible fertility problems and management aspects that could be improved.
Make recommendations to improve on present practices	
Discuss and make recommendations.	Recommend ways to overcome nutrient problems and to improve current practices.
Select recommendations.	Select the recommendation(s) with the household.
Test, evaluate and follow up on the recommendations	
Test the recommendation on the farm.	Choose and apply treatments with the household to test under farm conditions.
Monitor and evaluate the test with the farmer.	Evaluate the test results with the household.
Yield sampling.	Measure and compare yield in the different treatments.
Partial budget.	Calculate the cost and benefits of the different treatments. Assist the household to adopt/adapt the results and share them with other households.
Follow up the field test with the farmer.	Evaluate whether the recommended practices were suitable.
Disseminate the field test results.	Discuss a plan for follow-up action with other farmers in the village.

Table 7.2 Use this checklist to make sure that you talk to the appropriate person when asking questions about farm management and deciding on recommendations to test.

Activity	Who does the task?				Who makes the decisions?			
	H[a]	W	C	O	H	W	C	O
Fertilizer								
• Purchases fertilizers								
• Determines application rates								
• Applies fertilizer at planting								
• Applies fertilizer during cropping								
Livestock								
• Grazes livestock								
• Cuts/carries fodder from the field								
• Stall-feeds livestock								
• Handles animal manure in stall								
• Carries manure to the field								
• Applies manure to the crop								

Continued

Table 7.2 Continued.

Activity	Who does the task?				Who makes the decisions?			
	H[a]	W	C	O	H	W	C	O
Crops								
• Decides what crops are grown								
• Prepares soil for planting (ploughing, hoeing)								
• Manages crop residues (e.g. piled, returned to field)								
• Manages rice straw (e.g. burned, fed to cattle)								

[a]H = husband, W = wife, C = children, O = other.

Table 7.3 Questions to ask households in order to learn about farmer knowledge and better understand soil fertility management practices used on the farm.

Question	How can this information be used?
What is the land tenure status of your fields?	May indicate how much the farmer is willing to invest in soil fertility management (less likely for a tenant farmer).
What are good/poor properties of your soil?	Identify farmer's perception of soil characteristics (fertility, drainage, workability).
How does your soil fertility compare with other farms in the village/region? Explain why.	Identify general level of fertility.
What crops grow best here without a need for extra fertilizer?	Identify general level of fertility.
Do particular crops grow only on parts of the field? Why?	Identify poor and good areas of the field.
Has the soil fertility increased, decreased or stayed the same over the past 10 years? How do you know this?	Identify whether current practices are maintaining fertility.
Do you do anything to prevent soil erosion and surface water runoff?	Identify whether this is a problem and if it can be improved.
What do you do to improve soil fertility? Why?	Compare with principles described in this handbook.
What practices do you think decrease soil fertility? Why?	Compare with principles described in this handbook.

Table 7.4 Identify possible improvements to farmers' soil fertility management practices.

Practice	Yes/No
Timing of fertilization	
Is fertilizer applied at the correct time?	
Is fertilizer applied when there is sufficient soil moisture?	
Fertilizer application method	
Is fertilizer incorporated in the soil?	
Is fertilizer placed near the crop-plant root zone?	
Is fertilizer likely to damage the seed and/or seedling?	
Are compatible fertilizers being mixed?	
Balanced fertilization	
Is the most deficient nutrient applied?	
Organic material management	
Are crop residues returned to the soil?	
Are residues/ash spread evenly over the field?	
If livestock are being fed on vegetation that was grown on this field, is the manure being returned to the field?	
Is animal manure being applied to the field?	
Is animal manure stored properly?	

Continued

Table 7.4 Continued.

Practice	Yes/No
Fertilizer application rate	
Are recommended application rates being followed?	
Other practices	
Have soil conservation measures been installed?	
Is soil fertility being built up?	
Have practices to maintain soil fertility been adopted?	
Are animals integrated into the upland farm field?	
Are trees integrated in the upland farm field?	
Are legumes integrated into the upland farm field?	

Table 7.5 Use this table to summarize the results of your investigations on fertilizer use.

Question	Answer
What is the nutrient that most needs management improvement?	
Can fertilizer timing be improved?	
Can the fertilizer application method be improved?	
Can the balance between nutrients be improved?	
Can organic material management be improved?	
Can the fertilizer dose be improved?	
Are there any other practices that can be improved?	
1.	
2.	
3.	

Table 7.6 Examples of problems with soil fertility management and recommendations for improved practices that might be identified during discussions with farmers.

Problem	Recommendations
Farmer applies fertilizers at the wrong time.	1. Improve timing of fertilizer application. • Apply P and K fertilizers at planting. • Apply N fertilizers in split applications according to crop growth stage.
Farmer is not incorporating the fertilizer.	2. Improve method of fertilizer application. • Incorporate fertilizer to reduce leaching and volatilization losses. • Apply fertilizers near the crop root zone.
Farmer applies large amounts of N fertilizer but insufficient P and K fertilizer.	3. Introduce balanced fertilization. • Apply P and K fertilizers with N fertilizers in balanced applications (total quantity and cost of fertilizers is increased). • Reduce the amount of N fertilizer applied and increase the amount of K and P fertilizer applied (total quantity and cost of fertilizer remains the same). • Apply a large one-time application of P fertilizer to replenish soil P content.
Farmer burns cereal straw in one large heap in the corner of the field.	4. Improve organic material management. • Spread the straw before burning. • Spread the ash over the whole field before ploughing. • Arrange to burn in different parts of the field in successive seasons. • Do not burn the straw; incorporate when preparing the field for the next crop.
Residues are removed from the field to feed farmer's cattle.	5. Return animal manure to the field.
Fertilizer rates are below the economic optimum.	6. Optimize fertilizer application rates. • Increase the total amount of fertilizer applied.

Table 7.7 Yearly and daily dry matter intake and manure production by cattle, goats and buffaloes.

Species	Weight (kg)	Dry matter intake required		Manure produced	
		kg/year	kg/day	kg/year	kg/day
Cattle (moderate working)	350	11,000	30	2,700	7
Goat (medium activity)	40	1,200	3	440	1
Water buffalo (moderate working)	400	13,000	36	3,300	9

7.6 Soil fertility management

Table 7.8 Units and methods used for basic soil analysis.

Soil parameter	Units	Method used
pH (water)	pH	1:1 (soil:H_2O)
pH (KCl)	pH	1:1 (soil:1 M KCl)
Organic C	%	Wet oxidation (Walkley and Black)
Total N	%	Kjeldahl method
Available P	mg/kg	Bray II (molybdate blue) method, spectrophotometer
	mg/kg	Olsen method
Exchangeable K	cmol/kg	1 M NH_4Cl, pH 7, flame photometer
Exchangeable Na	cmol/kg	1 M NH_4Cl, pH 7, flame photometer
Exchangeable Ca	cmol/kg	1 M NH_4Cl, pH 7, atomic absorption spectrophotometer
Exchangeable Mg	cmol/kg	1 M NH_4Cl, pH 7, atomic absorption spectrophotometer
Exchangeable Al	cmol/kg	1 M KCl titration method
Exchangeable H	cmol/kg	1 M KCl titration method
Effective cation exchange capacity (ECEC)	cmol/kg	Exchangeable K+Na+Ca+Mg+Al+H
Al saturation	%	(Exchangeable Al/ECEC) x 100
Sand	%	Pipette method
Silt	%	Pipette method
Clay	%	Pipette method

Table 7.9 Critical values for some physical and chemical properties of upland soils.

Property	SI units	Value	Comments
Sand	%	>50	Leaching losses are likely to be large. Important to return crop residues to replenish soil organic matter, improve nutrient retention and soil moisture availability.
Clay	%	>45	Drainage problems likely. Large cation exchange capacity if clay is made up of 2:1 clay minerals. Large capacity to increase soil organic matter.
Clay	%	<30	Poor nutrient content; poor soil moisture retention; difficult to increase SOM.
pH (H_2O, 1:2.5 or 1.5)	–	<4.5	Liming may be required. No advantage from liming to pH >5.5.

Continued

Table 7.9 Continued.

Property	SI units	Value	Comments
pH (KCl, 1:2.5 or 1:5)	–	<4.2	Liming may be required. No advantage from liming to pH >5.5.
Organic C	%	<1.5	Poor nutrient retention, poor indigenous N supply. Poor soil physical properties (e.g. moisture availability, workability).
Total N	%	<0.15	Poor indigenous N supply.
Total P (HCl 25%)	mg/kg	<200	P deficiency likely. P inputs (fertilizers, farmyard manure) required.
P (Bray II)	mg/kg	<15	P deficiency likely. P inputs (fertilizers, farmyard manure) required.
Effective cation exchange capacity	cmol/kg	<10	Poor cation retention. SOM is an important source of cation exchange.
Exchangeable K	cmol/kg	<0.2	K deficiency likely. K inputs (fertilizers, farmyard manure) required.
Exchangeable Mg	cmol/kg	<0.2	Mg deficiency likely. Mg inputs (fertilizers, farmyard manure) required.
Exchangeable Ca	cmol/kg	<0.5	Ca deficiency likely. Ca inputs (fertilizers, farmyard manure) required.

Table 7.10 Major effects of pH in the soil.

Factor	Effect
Al toxicity	Al toxicity decreases with increasing pH.
P availability	P availability is greatest from pH 5.5 to 7.0.
Micronutrient availability (nutrients required in small amounts by plants)	All micronutrients, except Mo, are more available from pH 5.5 to 6.0 (Mn and Fe toxicity is minimized in this range).
Cation exchange capacity (the ability of a soil to retain cations such as Ca, Mg, K)	The cation exchange capacity increases with increasing pH in highly weathered soils. This means the soil is able to retain more Ca, Mg, K, which might otherwise be lost to leaching.
Nitrogen mineralization (the release of N from organic matter into plant-available forms)	Soil organisms required for N mineralization function best at soil pH 5.5–6.5.
N_2-fixation (the conversion of N_2 from the atmosphere into forms that can be used by plants)	N_2-fixing nodules are less likely to occur and function less effectively at pH >5.0.
Disease	Some diseases can be controlled by manipulating soil pH (e.g. potato scab incidence decreases with decreasing pH).
Phosphate rock (PR) dissolution	Soil pH must be <5.5 for PR to dissolve and release P for plant uptake.

Table 7.11 Effect of some management practices on SOM.

Practice	Effect
Reduce soil erosion	Reduces losses of SOM.
Reduce tillage intensity	Slower rate of SOM decomposition.
Residue quality (C/N ratio)	Residues with a wide C/N ratio (e.g. rice straw) are less effective than those with a narrow C/N ratio (e.g. groundnut leaves) in maintaining SOM. Much of the carbon in low-N residues is oxidized and released as CO_2, and the amount of SOM created is therefore small.
Crop residues returned to the field	Provides raw material for SOM replenishment. If residues are required to feed livestock, animal manure should be returned to the soil.

Table 7.12 Important factors for managing N, P and S in upland soils.

Nutrient	Important management factors
Nitrogen	• Reduce leaching losses. • Increase biological N_2-fixation (BNF). • Maintain or increase SOM. • Use N fertilizers efficiently. • Return crop residues to the field. • Do not burn crop residues.
Phosphorus	• Add P to soil as fertilizer. • Maintain SOM. • Increase P-use efficiency by applying P fertilizers together with readily decomposable organic residues and animal manures.
Potassium	• Reduce leaching losses. • Return crop residues and animal manure from livestock fed with fodder taken from the field. • Add K fertilizers to the soil.
Magnesium	• Return crop residues and animal manure from livestock fed with fodder taken from the field. • Add Mg fertilizer or dolomite to the soil.
Calcium	• Return crop residues and animal manure from livestock fed with fodder taken from the field. • Add Ca fertilizers or lime to the soil.
Sulfur	• Return crop residues. • Maintain SOM. • Do not burn crop residues.

Table 7.13 Sources of nutrients for soil rehabilitation.

Source	Advantage	Disadvantage
Mineral fertilizer and lime	Easy to transport and apply. Rapid effect.	Costly. May not be available locally in remote areas.
Animal manure, compost and crop residues obtained from off-farm sources	In addition to nutrients, organic manures provide material for SOM replenishment.	May not be available locally or in sufficient quantity. May be very costly. Difficult to handle and transport.
Biological N_2-fixation (BNF)	Atmospheric N_2 is fixed and brought into the farm.	P and K fertilizer may be required to increase BNF on acid, upland soils.
Rainfall	Nutrients added at no cost.	Insufficient amounts.
Nutrients contained in surface runoff and eroded soil carried into the farm	Nutrients added at no cost.	Neighbour's farm has become eroded, resulting in reduced stability in the farming community.
Nutrients taken up by deep-rooting crops or plants and deposited at the soil surface in leaf litter and crop residues	Nutrients may be added at no cost.	Difficult to find a suitable plant species that produces a marketable product and has roots that are tolerant of Al toxicity. The amount of nutrients in the subsoil is very small.

Table 7.14 Some myths and facts about biological soil fertility management.

Myth	Fact
Fallow vegetation adds nutrients to the soil.	Fallow vegetation returns nutrients to the soil that may have been absorbed from beneath the crop rooting zone.
Nutrients are added to the soil in prunings from alley and contour strip hedgerow prunings.	When properly nodulated, N_2-fixing legume fallow species add N to the soil through root decay and above-ground litter inputs. Other nutrients (P, K, Mg) are recycled, not added.
Legumes growing in mixed cropping systems provide N to the companion crop.	By fixing part of their N requirements, legumes *spare* soil N for uptake by non-N_2-fixing crop plants.

Continued

Table 7.14 Continued.

Myth	Fact
Soil organic matter (SOM) is increased by returning crop residues to the soil.	The carbon returned to the soil in crop residues may not be sufficient to replace the depletion of SOM in agricultural soils due to decomposition. Returning crop residues to the soil may reduce the rate of decrease in SOM in cultivated soils.

Table 7.15 Methods to overcome soil fertility factors that inhibit N_2-fixation.

Factor inhibiting N_2-fixation	Recommendation
High soil N status	Either don't apply starter N or apply only small amounts (<10 kg/ha N fertilizer) to legume crop plants at planting.
Low soil P status	Apply P fertilizer to crop rooting zone.
Low soil pH (<5.0–5.5), except for cowpea	Apply lime to crop rooting zone.
Low soil Mo status (nodules large and green on inside, but inactive)	Apply fertilizer containing Mo.

Table 7.16 Legume genera and compatible rhizobia.

Rhizobia genus	Plant type	Legume genera inoculated
Bradyrhizobium ('slow-growing' rhizobia)	Cover plants	*Calopogonium*, *Centrosema*, *Desmodium*, *Pueraria*, *Stylosanthes*
	Grain legumes	*Arachis*, *Cajanus*, *Glycine*, *Phaseolus*, *Vigna*
	N_2-fixing trees	*Acacia*, *Prosopsis*
Rhizobium ('fast growing' rhizobia)	Grain legumes	*Cajanus*, *Phaseolus*
	N_2-fixing trees	*Calliandra*, *Gliricidia*, *Leucaena*, *Prosopsis*, *Sesbania*

Table 7.17 Principles and methods to reduce soil erosion.

Principles	Methods
Reduce detachment of soil particles	
Protect soil from direct raindrop impact	Apply a mulch and use crop residues, tree leaf clippings.
Reduce the force of raindrops	Leaves help to reduce the force of a raindrop's impact at the soil surface. For this reason, maintaining a continuous plant cover over the soil can help to reduce erosion.
Reduce soil transport	
Reduce the speed of water[a]	Shorten the length of the slope. The longer the slope the faster the water can move. In one example, doubling the length of a 9% slope increased soil loss twofold.
	Use physical barriers such as grass strips, crop residues, tree stumps, logs, ridge terraces.
	Reduce the steepness of the slope with the natural terraces formed from stone retention walls, grass barriers, contour bunds.
Increase water infiltration	Mix crop residues with the soil. Apply animal manure to improve soil structure. This can increase the amount of water infiltration and reduce the amount of water that runs down the slope.
	Provide a rough surface by carrying out light tillage. Apply crop residues.

[a]By halving the speed of water flowing down a slope:
- the maximum size of particle that it carries is reduced 64-fold;
- the erosive power of the water is reduced fourfold; and
- the amount of material that can move in the water is reduced 32-fold.

Table 7.18 Nutrient content (%) of manures and residues commonly available in SSA.

Material	Water	C	N	P	K	Ca
Human faeces	–	–	1.0	0.2	0.3	–
Cattle faeces	–	–	0.3	0.1	0.1	–
Pig faeces	–	–	0.5	0.2	0.4	–
Fresh cattle manure	60	8–10	0.4–0.6	0.1–0.2	0.4–0.6	0.2–0.4
Composted cattle manure	35	30–35	1.5	1.2	2.1	2
Farmyard manure	50	–	1.0	0.8	1.2	0.8
Goat manure	50	–	0.8	0.7	1.5	0.8
Sheep manure	50	–	1.0	0.7	1.5	1.7
Pig manure	80	5–10	0.7–1.0	0.2–0.3	0.5–0.7	1.2
Poultry manure	55	15	1.4–1.6	0.25–0.8	0.7–0.8	2.3
Garbage compost	40	16	0.6	0.2	2.3	1.1
Sewage sludge	50	17	1.6	0.8	0.2	1.6
Sugarcane filter cake	75–80	8	0.3	0.2	0.06	0.5
Castor bean cake	10	45	4.5	0.7	1.1	1.8

7.7 Crop nutrition

Table 7.19 Symbols and atomic weights for elements involved in plant nutrition.

Name	Symbol	Atomic weight	Name	Symbol	Atomic weight
Aluminium	Al	26.79	Manganese	Mn	54.93
Boron	B	10.82	Molybdenum	Mo	95.95
Calcium	Ca	40.08	Nitrogen	N	14.01
Chlorine	Cl	35.46	Nickel	Ni	58.69
Cobalt	Co	58.94	Oxygen	O	16.00
Copper	Cu	63.57	Phosphorus	P	30.89
Fluorine	F	19.00	Potassium	K	39.10
Hydrogen	H	1.01	Sodium	Na	23.00
Iodine	I	126.92	Sulfur	S	32.06
Iron	Fe	55.85	Zinc	Zn	65.38
Magnesium	Mg	54.93	Silicon	Si	28.06
Carbon	C	12.01	Selenium	Se	78.96

Table 7.20 Functions of essential plant nutrients (other than C, H and O) and their relative mobility in plants and soils.

Essential plant nutrient	Important functions and roles in the plant	Plant dry matter (%)	Mobility[a]	
			Plant	Soil
Macronutrients				
Nitrogen (N)	Protein formation, photosynthesis.	1.5	5	5
Phosphorus (P)	Energy storage/transfer, root growth, crop maturity, straw strength, disease resistance.	0.2	5	1
Potassium (K)	Plant turgor pressure maintenance, accumulation and transport of the products of plant metabolism, crop disease resistance.	1.0	5	3–4
Magnesium (Mg)	Photosynthesis.	0.2	5	2
Sulfur (S)	Many functions. In compounds that provide odour in onions.	0.1	2	5
Calcium (Ca)	Cell growth and walls, required by groundnut for nut development.	0.5	1	2–3

Continued

Table 7.20 Continued.

Essential plant nutrient	Important functions and roles in the plant	Plant dry matter (%)	Mobility[a]	
			Plant	Soil
Micronutrients				
Chloride (Cl)	Photosynthesis, early crop maturity, disease control.	0.01	5	5
Iron (Fe)	Photosynthesis and respiration.	0.01	2	2
Manganese (Mn)	Photosynthesis, enzyme function.	0.005	–	2
Boron (B)	Development/growth of new cells.	0.002	1	3
Zinc (Zn)	Enzymatic activity.	0.002	2	2
Copper (Cu)	Chlorophyll and seed formation, protein synthesis.	0.0005	2	2
Molybdenum (Mo)	Legume N_2-fixation, nitrate reduction.	0.00001	2	2

[a]1 = poor mobility, 5 = very mobile. Compare mobility within columns.

Table 7.21 Nutrient removal in selected cereals, root crops, food legumes and fodder crops.

Crop	Product	Removal (kg/t crop product)					
		N	P	K	Mg	Ca	S
Cereals							
Maize hybrid	Grain	15.6	2.9	3.8	0.4	0.9	1.3
Maize local	Grain	16.0	2.8	4.0	0.4	0.8	1.2
Rice improved	Grain	15.0	2.8	3.8	0.3	1.0	0.8
Rice local	Grain	15.0	2.5	2.5	0.5	1.0	0.5
Sorghum	Grain	16.5	3.5	3.8	1.9	0.4	1.2–1.6
Millet	Grain	26.6	3.5	4.4	1.3	0.1	1.2
Root crops							
Cassava	Roots	1.7	0.5	2.5	0.4	0.2	0.2
Taro	Tubers	3.0	0.6	2.9	0.3	0.4	0.3
Potato	Tubers	2.7	0.3	3.6	0.3	0.3	0.3
Sweet potato	Tubers	3.8	0.5	5.3	0.4	0.5	0.3
Yam	Tubers	1.5	0.4	2.5	0.2	0.1	0.1
Food legumes							
Beans	Beans	28.3	3.0	14.0	2.0	1.3	1.0
Cowpea	Grain	55.0	5.0	21.0	4.0	4.0	6.0
Groundnut	Grain	32.0	3.2	4.8	1.6	1.6	1.2
Mungbean	Grain	55.0	4.0	17.0	4.0	3.0	2.0
Soybean	Grain	50.0	4.0	15.3	2.7	2.7	2.0
Fodder crops							
Grass	Dry matter	30.0	3.7	26.7	7.2	5.0	4.2
Legumes	Dry matter	37.5	4.4	33.3	13.4	5.3	5.0

Table 7.22 Common nutrient deficiencies in acid, upland soils and their effects on crop growth.

Soil status	Effect on crop growth
Low soil phosphorus status	Many crops, especially legumes, do not grow well in low P-status soils. Usually, P must be added in the form of a mineral fertilizer such as TSP or rock phosphate. Where cropping systems are planned to rely on biological N_2-fixation, P deficiency often limits the supply of N to crop plants indirectly.
Low soil nitrogen status	The soil N supply depends on the amount of soil organic matter (SOM). The greater the amount of SOM, the more N that the soil can supply to plants. Low soil N reduces the growth of all non-legume plants (e.g. cereals), and almost all crops benefit from some N inputs.

Continued

Table 7.22 Continued.

Soil status	Effect on crop growth
Low soil potassium status	Potassium usually becomes deficient in soils that have been cropped for several seasons or years without the use of K fertilizers, such as KCl. In many crops, most of the K taken up by the plant is contained in crop residues and therefore K deficiency is more likely to occur where crop residues are removed from the field.
Low soil calcium status	Many crops can grow in low Ca status soils, but some crops (e.g. groundnut) do not form properly developed pods/shells in low Ca status soils. Calcium is usually applied in liming materials such as agricultural lime, calcite or dolomite.
Low soil magnesium status	Magnesium usually only becomes a problem in soils that have been cropped for several seasons or years without the addition of Mg fertilizers (e.g. dolomite, langbeinite, kieserite). Mg deficiency is more common where crop residues are removed from the field.
Low soil micronutrient status (Zn, B, etc.)	Micronutrients are nutrients that are required by the plant in relatively small quantities. The correction of micronutrient deficiencies usually becomes more important if a field has been intensively cropped for several years without the addition of micronutrients.

Table 7.23 Some conditions in which nutrients may limit crop growth in acid, upland soils.

Nutrient	Conditions where nutrient becomes limiting
P	Most upland soils that have not received significant amounts of P fertilizer.
N	When large amounts of straw have been applied; when SOM status is low; or when high N-demanding, non-N fixing crops (e.g. maize, rice) are grown without fertilizer.
K	When a soil has been cropped for several seasons with little or no addition of K fertilizer (occurs more readily when crop residues are not returned to the soil); when Ca-containing fertilizers are applied.
Mg	As for K.
S	When crop residues are not returned; when S-containing minerals are not applied (e.g. ammonium sulfate, langbeinite, kieserite, dolomite).
Ca	Seed formation is often poor in groundnuts grown on acid soils.

Table 7.24 Identification of nutrient problems. The more times you answer 'yes' for a nutrient, the more likely that its management needs to be improved.

Criteria	Yes/No
N deficiency	
Are N nutrient deficiency symptoms present?	
Does the nutrient budget indicate N removal?	
Are non-legume crops usually planted?	
Are crop yields lower than the average yields in the region?	
P deficiency	
Are P nutrient deficiency symptoms present?	
Have any large applications of P been done during the last 5 years?	
Does the nutrient budget indicate more P is removed than is applied?	
Are crop yields lower than average, good yields in the region?	
Is the soil pH <5.5?	

Continued

Table 7.24 Continued.

Criteria	Yes/No
K and/or Mg deficiency	
Are K and/or Mg nutrient deficiency symptoms present?	
Is the crop residue usually removed or not evenly returned to the field?	
Has the field been cropped for many years?	
Does the nutrient budget indicate K and/or Mg removal?	
Have crop yields been steadily declining?	
Is there a wide ratio between the amount of exchangeable Ca and Mg in the soil?	

Table 7.25 Characteristics of leaf nutrient deficiencies.

Nutrient	Position on plant	Chlorosis?	Leaf margin necrosis?	Colours and leaf shape
N	All leaves	Yes	No	Yellowing of leaves and leaf veins
P	Older leaves	No	No	Purplish patches
K	Older leaves	Yes	Yes	Yellow patches
Mg	Older leaves	Yes	No	Yellow patches
Ca	Young leaves	Yes	No	Deformed leaves
S	Young leaves	Yes	No	Yellow leaves
Mn, Fe	Young leaves	Yes	No	Inter-veinal chlorosis
B, Zn, Cu, Ca, Mo	Young leaves	–	–	Deformed leaves

Table 7.26 The mobility of nutrients in plant and soil can be used to understand nutrient deficiency systems in plants, and fertilizer management in soils.

	Less mobile	More mobile
Plant	Deficiency symptoms first appear on younger leaves (S, Ca, Zn, Fe, Cu, B). When nutrient uptake is limited, less mobile nutrients are not moved from older leaves to support new growth in younger leaves.	Deficiency symptoms first appear on older leaves (N, K, P, Mg). When nutrient uptake is limited, more mobile nutrients are moved from older leaves to support growth in younger leaves
Soil	Less mobile nutrients are more likely to remain near to where they were applied except if the soil particles are physically mixed by tillage or carried away by wind or water (P).	More mobile nutrients are more easily lost due to leaching and volatilization (N, K, Mg, Ca). Care must be taken to reduce losses of these nutrients.

Table 7.27 Comparison of nutrient removal in local and improved varieties.

Crop	Yield (t/ha)		Grain (kg/ha)			Straw (kg/ha)		
	Grain	Straw	N	P	K	N	P	K
Improved rice variety	4	4	48	10	24	24	6	160
Local rice variety	1	2	18	4	5	12	1	50
Difference	3	2	30	6	19	12	5	110

Table 7.28 There are three main categories of nutrient availability, because not all of the nutrients in an upland field can be immediately used by plants.

Availability	When available to plants	Examples
Readily available to plants.	Immediately or during the current annual crop.	Nutrients contained in soluble fertilizers (e.g. KCl), readily mineralized SOM, nutrients held on the edges of soil particles, and in the soil solution.

Continued

Table 7.28 Continued.

Availability	When available to plants	Examples
Slowly available to plants.	During the current annual crop or within the next few crops.	Nutrients contained in organic form, such as plant residues and organic manures (particularly where the C/N ratio is wide), slowly soluble mineral fertilizers (e.g. phosphate rock), and the SOM fraction that is resistant to mineralization.
Not available to plants.	Probably not during farmer's lifetime.	Nutrients contained in rocks, or adsorbed on soil particles.

Table 7.29 Micronutrients concentration in soils, and pH ranges for maximum availability.

Micronutrient	Symbol	Total content (mg/kg)	Optimum pH range
Boron	B	10–630	5.0–7.0
Cobalt	Co	1–40	5.0–5.5
Copper	Cu	1–960	5.0–6.5
Chlorine	Cl	5–800	Not affected
Iron	Fe	3,000–100,000	4.0–6.0
Manganese	Mn	30–5,000	5.0–6.5
Molybdenum	Mo	0.1–18	6.0–8.5
Zinc	Zn	2–1,600	5.0–6.5

Table 7.30 Factors contributing to micronutrient toxicities, toxicity symptoms and toxicity levels in plants.

Micronutrient	Toxicity factors	Toxicity symptoms	Toxicity levels (mg/kg)
B	Large applications of urban compost.	Chlorosis and necrosis of leaf tips and leaf margins.	>200
Co	Soils (sandy, highly calcareous, peaty). Fe/Al/Mn oxides. Liming, drainage.	Not known (still unclear whether Co has a direct function in plants).	>1000 (some species >4000)
Cu	Contamination of soils due to large applications of slurries and urban compost.	Chlorosis and necrosis of older leaves. Inhibition of root elongation.	>20
Cl	Poorly drained coastal soils and salt-affected areas, salt tolerance of species.	Leaf scorching and growth inhibition (especially in salt-sensitive cultivars).	>3500
Fe	Submerged soils, waterlogged areas.	Bronzing in rice, and purple discoloration of leaves in other crops.	>500
Mn	Submerged soils, waterlogged areas.	Brown spots on leaf veins, necrosis starting at leaf tips and margins, leaf crinkling.	>500
Mo	Liming in addition to Mo application.	Golden to orange-yellow (sometimes purple) discoloration.	>1000
Zn	Under glass and screen house roofs.	Rarely occurs.	>400

Table 7.31 Tolerance to Al saturation in various crops.

Crop	Latin name	Low	Moderate	High
		0–40%	40–70%	>70%
Maize	*Zea mays*	X		
Mungbean	*Vigna radiata*	X		
Groundnut	*Arachis hypogaea*	X	X	
Cowpea	*Vigna unguiculata*		X	X
Soybean	*Glycine max*	X		
Upland rice	*Oryza sativa*		X	X

Continued

Table 7.31 Continued.

Crop	Latin name	Low	Moderate	High
		0–40%	40–70%	>70%
Cassava	*Manihot esculenta*			X
Brachiaria	*Brachiaria* spp.			X
Setaria	*Setaria* spp.		X	
Crotolaria	*Crotolaria* spp.	X		
Mucuna	*Mucuna puriens*		X	X

7.8 Fertilizer use

Table 7.32 Nutrient conversion factors.

From	Multiply by	To get/From	Multiply by	To get
NO_3	0.226	N	4.426	NO_3
NH_3	0.823	N	1.216	NH_3
NH_4	0.777	N	1.288	NH_4
$CO(NH_2)_2$ – urea	0.467	N	2.143	$CO(NH_2)_2$ – urea
$(NH_4)_2SO_4$	0.212	N	4.716	$(NH_4)_2SO_4$
NH_4NO_3	0.350	N	2.857	NH_4NO_3
P_2O_5	0.436	P	2.292	P_2O_5
$Ca_3(PO_4)_2$	0.458	P_2O_5	2.185	$Ca_3(PO_4)_2$
K_2O	0.830	K	1.205	K_2O
KCl	0.632	K_2O	1.583	KCl
KCl	0.524	K	1.907	KCl
K_2SO_4	0.541	K_2O	1.850	K_2SO_4
K_2SO_4	0.449	K	2.229	K_2SO_4
$ZnSO_4.H_2O$	0.364	Zn	2.745	$ZnSO_4.H_2O$
$ZnSO_4.7H_2O$	0.227	Zn	4.398	$ZnSO_4.7H_2O$
SO_2	0.500	S	1.998	SO_2
SO_4	0.334	S	2.996	SO_4
$MgSO_4$	0.266	S	3.754	$MgSO_4$
$MgSO_4.H_2O$	0.232	S	4.316	$MgSO_4.H_2O$
$MgSO_4.7H_2O$	0.130	S	7.688	$MgSO_4.7H_2O$
$(NH_4)_2SO_4$	0.243	S	4.121	$(NH_4)_2SO_4$
SiO_2	0.468	Si	2.139	SiO_2
$CaSiO_3$	0.242	Si	4.135	$CaSiO_3$
$MgSiO_3$	0.280	Si	3.574	$MgSiO_3$
MgO	0.603	Mg	1.658	MgO
MgO	2.987	$MgSO_4$	0.355	MgO
MgO	3.434	$MgSO_4.H_2O$	0.291	MgO
MgO	6.116	$MgSO_4.7H_2O$	0.164	MgO
MgO	2.092	$MgCO_3$	0.478	MgO
CaO	0.715	Ca	1.399	CaO
$CaCO_3$	0.560	CaO	1.785	$CaCO_3$

Continued

Table 7.32 Continued.

From	Multiply by	To get/From	Multiply by	To get
$CaCl_2$	0.358	Ca	2.794	$CaCl_2$
$CaSO_4$	0.294	Ca	3.397	$CaSO_4$
$Ca_3(PO_4)_2$	0.388	Ca	2.580	$Ca_3(PO_4)_2$
$FeSO_4$	0.368	Fe	2.720	$FeSO_4$
$MnSO_4$	0.364	Mn	2.748	$MnSO_4$
$MnCl_2$	0.437	Mn	2.090	$MnCl_2$
$MnCO_3$	0.478	Mn	2.092	$MnCO_3$
MnO_2	0.632	Mn	1.582	MnO_2
$CuSO_4.H_2O$	0.358	Cu	2.795	$CuSO_4.H_2O$
$CuSO_4.5H_2O$	0.255	Cu	3.939	$CuSO_4.5H_2O$
$Na_2B_4O_7.5H_2O$	0.138	B	7.246	$Na_2B_4O_7.5H_2O$
$Na_2B_4O_7.7H_2O$	0.123	B	8.130	$Na_2B_4O_7.7H_2O$

Table 7.33 Nutrient content (%) of fertilizers commonly available in SSA.

Fertilizer	Abbreviation	N	P_2O_5	K_2O	MgO	CaO	S	Other
Urea	–	46						
Ammonium chloride	AC	25						66 Cl
Ammonium nitrate	AN	34						
Calcium nitrate	CN	15				26		
Calcium ammonium nitrate	CAN	27			2	4		
Ammonium sulfate	AS	21					24	
Mono ammonium phosphate	MAP	11	48–55		0.5	2	1–3	
Diammonium phosphate	DAP	18–21	46–53				1–1.5	
Phosphate rock	PR		25–41			25–50		
Fused magnesium phosphate	FMP		12–20		10–15	12–16		
Single superphosphate	SSP		16–22			28	11–14	
Double superphosphate	SP36		32–36				5–6	
Triple superphosphate	TSP		44–53		0.5	12–19	1–1.5	
Potassium chloride	KCl		60–62					47 Cl
Potassium sulfate	SOP			50–53			17–18	
Potassium nitrate	KN	13		44	0.5	0.5	0.2	
Kieserite	Kies				27		22	
Langbeinite	SKMg			22	18		22	
Dolomite	GML				10–22	35–45		
Agrilime (calcite)	–					47		
Gypsum	–					22–30	13–16	
NPK 15–15–15	–	15	15	15				
NPK 16–16–8	–	16	16	8			1	
NPK 13–13–21	–	13	13	21				
NPK 12–12–17+2 (Mg) + (trace elements)	–	12	12	17	2			Micro
NPK 15–15–6+4 (Mg)	–	15	15	6	4			
NPK 5–18–10		5	18	10			8	
NPK 5–17–15		5	17	15				
NPK 8–14–7		8	14	7				

Table 7.34 Guide for mixing straight fertilizers available in SSA.

	Calcium sulfate	Dolomite	Limestone	PR	NPK (urea-based)	NPK (ammonium nitrate-based)	Potassium sulfate	Potassium chloride	Diammonium phosphate	Triple superphosphate (TSP)	Single superphosphate	Calcium ammonium nitrate	Ammonium sulfate	Ammonium nitrate
Urea						1		6		3	3	1		1
Ammonium nitrate					1	7		7		4	4		2	
Ammonium sulfate						7						2		
Calcium ammonium nitrate					1	7		7		5	5			
Single superphosphate	4	4	4		4	4			4					
Triple superphosphate (TSP)	4	4	4		4	4			4					
Diammonium phosphate														
Potassium chloride						7								
Potassium sulfate														
NPK (ammonium nitrate-based)					1									
NPK (urea-based)														
PR														
Limestone														
Dolomite														

Key

Can be mixed and stored.

Can be mixed and stored for 2–4 days only.

Cannot be mixed – incompatible!

Explanatory notes

1 Mixture absorbs water, becomes a wet slurry and is difficult to store and apply.

2 Mixture can become explosive!

3 TSP reacts with urea and releases water resulting in a wet mixture that cakes on drying.

4 TSP is produced by treating PR with acid. Free acid may react with other mixture components.

5 Mixture may become wet and then cake on drying.

6 Mixture may absorb water and become caked and difficult to apply.

7 Mixture could decompose.

Table 7.35 Nutrient content of secondary nutrient fertilizer sources.

Nutrient	Material	Concentration
Sulfur	Ammonium sulfate	24% S
	Single superphosphate	12% S
	Potassium sulfate	18% S
	Ammonium phosphate sulfate	15% S
	Gypsum	13–18% S
	Pyrites	22–24% S
	Mineral sulfur	84–100% S
	Sulfate of magnesium	13% S
	All salts containing sulfur	13–19% S
Calcium	Limestone	80–95% $CaCO_3$
	Dolomite	24–45% CaO
	Gypsum	40% CaO
	SSP (single simple superphosphate)	25–30% CaO
	PR	39–48% CaO
	Limestone	54% CaO
	Calcium ammonium nitrate	10–20% CaO
Magnesium	Magnetite	40% MgO
	Magnesium sulfate	16% MgO
	Mg chelated	2–10% MgO
	Dolomite	5–20% MgO
Boron	Boric acid	17.5% B
	Solubor	20.5% B
	Boronated single superphosphate (SSP)	0.18% B
Copper	Copper sulfate	24% Cu
	Cu chelated	5–12% Cu
Iron	Iron sulfate	19% Fe
	Chelated compounds	5–10% Fe
	Chelated iron (FCO)	12% Fe
Manganese	Sulfate of manganese	30.5% Mn
	Chelated compounds	5–12% Mn
Molybdenum	Ammonium molybdenum	54% Mo
Zinc	Zn sulfate	21% Zn
	Monohydrate zinc sulfate	33% Zn
	Chelated Zn (FCO)	12% Zn
	Other compounds	4–13% Zn
Chlorite	Potassium chloride	48% Cl
All	Compound fertilizer NPK	Various

Table 7.36 Timing of fertilizer application in relation to soil properties, climate and crop requirements.

	Soil	Climate	Annual crops	Perennial crops
N	Nitrate (NO_3^-) leaching in low-pH, light-textured, well-drained soils. Ammonia (NH_3) volatilization larger with increasing pH.	Increased leaching during periods of high rainfall. Increased nitrification during periods of high temperature.	Increased supply needed at young stage, flowering and during peak stages.	Supply in line with weather and crop cycle.
P	Strong sorption (fixation) in fine-textured Fe/Mn/Al-oxide-containing acid soils. Unavailable at high pH due to precipitation with Ca.	Increased losses of surface applied P by runoff and erosion during high-rainfall events and periods.	Before or at planting incorporated with soil near the surface.	During land preparation incorporated with soil near surface and/or near the planting hole.
K	Light-textured and well-drained soils poor in SOM may be prone to leaching. Illitic minerals in some tropical soils may cause fixation of K.	Increased potential of leaching, runoff and erosion during high-rainfall periods. Well-supplied crops can withstand dry periods better.	Before or at planting incorporated with soil near the surface. Large application rates (e.g. >120 kg K_2O/ha) should be split (e.g. 50% basal plus 1–2 top dressings).	Regular supply in line with weather and crop cycles.

Table 7.37 Fertilizer recommendations for selected crops based on crop requirements.[a]

Crop	Amount of nutrients required for production of 1 t of edible yield (kg)		
	N	P_2O_5	K_2O
Banana	7.1	2.1	20.1
Beans	69.6	20.0	55.1
Cabbage	4.2	1.1	3.7
Cassava	10.4	2.4	6.8
Citrus	1.5	0.4	2.5
Coffee	76.9	12.4	86.6
Cotton	105.3	43.9	112.0
Groundnut	57.3	12.1	26.3
Maize	28.1	11.2	49.5
Oil palm	11.8	3.8	13.3
Potato	5.9	2.5	10.7
Sorghum	42.2	19.5	70.2
Sugarcane	1.3	0.4	2.9
Sunflower	37.4	24.9	110.0
Soybean	79.0	14.0	36.0
Tea	40.0	26.4	28.9
Rice	23.3	9.1	37.3
Wheat	28.3	10.5	32.7

[a]These values do not take into consideration soil nutrient losses.

Table 7.38 Characteristics of major phosphate rock sources available in SSA.

Country	Place	Total P_2O_5	% P_2O_5 soluble in 2% CAS	% P_2O_5 soluble in 2% FAS	CaO (%)
Australia	Christmas Island	34	12	12	36
China	Yunnan	35	14	8	44
Indonesia	Gresik	28	4	n.a.	43
Jordan	El Hassa	33	11	15	50
Morocco	Khourigba	33	11	17	51
Tunisia	Gafsa	30	9	22	47

Continued

Table 7.38 Continued.

Country	Place	Total P_2O_5	% P_2O_5 soluble in 2% CAS	% P_2O_5 soluble in 2% FAS	CaO (%)
USA	Florida	31	5	7	46
USA	North Carolina	35	13	25	49

[a]CA = citric acid, FA = formic acid.

Table 7.39 Required properties of PR for direct application.

Property	Minimum standard (%)	Comment
Content • Total P_2O_5 • CaO	 >25 >40	Solubility indicates the amount of P that is released for plant uptake. CaO content affects liming properties.
Solubility • 2% citric acid (CA) • 2% formic acid (FA)	 >8.2 >14	Total P_2O_5 must be assessed in relation to solubility.
Fineness • Passing 80-mesh sieve • Passing 50-mesh sieve	 >80 >50	The finer the material, the larger the surface area for reaction with the soil solution.
Moisture content	<2	Damp material is difficult to spread.
Heavy metal content		Small amounts of heavy metals (e.g. Cd, Pb, Ni) in rock phosphates and their potential accumulation in soils due to P fertilizer application is a matter of environmental concern. In South-east Asia, to date, comparable contents of heavy metals have been found in fertilized and unfertilized soils. Uranium in sedimentary deposits formed under fresh water can be problematic for mine workers.

7.9 Crop agronomy

Table 7.40 Recommended planting densities for major crops grown under favourable and marginal rainfall.[a]

	High rainfall				Poor rainfall			
	Between rows (cm)	Within rows (cm)	Plants per stand	Density ('000 plants ha^{-1})	Between rows (cm)	Within rows (cm)	Plants per stand	Density ('000 plants ha^{-1})
Maize	75	25	1	53	90	30	1	37
Soybean	45	5	1	444	45	15	1	148
Beans	50	10	1	200	50	15	1	133
Rice	20	20	2	500	30	30	2	222
Sorghum	75	15	1	888	90	15	1	74

[a]These are meant to be general guidelines.

7.10 Farm economics

Table 7.41 Example of a partial budget analysis for comparing the recommended fertilizer dose with the farmer's practice for groundnut.

Additional income per hectare from recommended practice		$
Recommended practice	1.25 t groundnut @ $60/t	75
Farmer's practice	0.5 t groundnut @ $60/t	30
Net additional income A		45

Table 7.41 Continued.

Additional income per hectare from recommended practice		$
Materials	Additional fertilizer required	
	25 kg urea @ $ 0.2/kg	5
	50 kg TSP @ $ 0.3/kg	15
	25 kg KCl @ $ 0.4/kg	10
Labour	1 man-day labour for spreading @ $5/man-day	5
Total additional costs B		35
Margin over additional costs from using recommended practice (A – B)		10

7.11 General

Table 7.42 Equipment required for working with soils in the field.

Equipment	Positioning	Sampling	
		Soil profile	Top soil
Tape measure	X		
Clinometer	X		
GPS kit	X		
Map and aerial photo	X		
Shovel/spade		X	
Hoe		X	
Cutlass		X	
Edelman auger			X
Writing board, pencil and eraser		X	X
Munsell soil colour chart		X	
Knife		X	X
Hand lens		X	
Wash bottle (H_2O)		X	X
pH kit		X	X
HCl		X	X
Bucket, sample bags and pens		X	X
Sample pots		X	
Field bag		X	X
Manuals		X	X

7.12 Reading list

This reading list is provided as a lead into recent literature. Each citation is followed by comments and explanation of the citation in *italics*. Where the source is downloadable, a link is provided.

Anderson, J.M. and Ingram, J.S.I. (1993) *Tropical Soil Biology and Fertility. A Handbook of Methods*, 2nd edn. CAB International, Wallingford, UK.

A handbook providing methods for soil fertility research.

Dierolf, T.S., Fairhurst, T.H. and Mutert, E.W. (2001) *Soil Fertility Kit: a Toolkit for Acid, Upland Soil Fertility Management in Southeast Asia*. Potash & Phosphate Institute (PPI), ProRLK, GTZ GmbH, Singapore.

Source of Tables 7.2 to 7.4, 7.6 to 7.33, 7.36, 7.38, 7.39, 7.41 and 7.42.

EFMA (2006) *Guidance for the Compatibility of Fertilizer Blending Materials*. European Fertilizer Manufacturers Association, Brussels.

Information on mixing fertilizer materials.

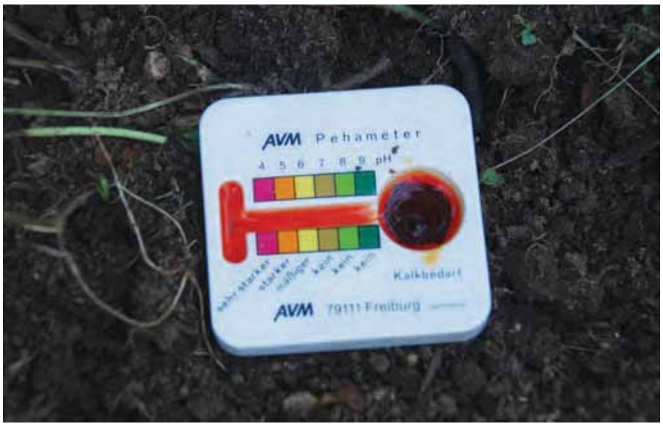


Photo 7.1 A Pehameter® is a useful low-cost tool for measuring soil pH in the field.

Photo 7.2 Leaf colour charts can be used to improve the timing of N fertilizer top dressings in rice.

Photo 7.3 An Edelman soil auger is an essential tool for soil sampling.

Glossary

Adulterate: Make poor in quality by adding another substance, especially related to fertilizers.

Agroecology: The science of applying ecological concepts and principles to the design and management of sustainable agroecosystems (source: http://www.agroecology.org/glossary.html).

Agroforestry: Multiple cropping land-use systems that involve the production of agricultural crops and trees on the same piece of land in a complementary manner. A simpler definition is 'trees on farms' (source: http://en.wikipedia.org/wiki/Agroforestry).

Agronomic efficiency: The additional amount of yield obtained per kilogram of nutrient added. The difference between yield in a control plot and in a plot supplied with nutrients divided by the amount of the given nutrient added. The agronomic efficiency is calculated for each nutrient separately.

Agronomy: The theory and practice of crop production and soil management.

Arbuscular mycorrhizal fungi: A type of mycorrhiza in which the fungus penetrates the cortical cells of the roots of a vascular plant. Mycorrhiza improve the uptake of nutrients, particularly phosphorus, by the host plant (source: http://en.wikipedia.org/wiki/Arbuscular_mycorrhiza).

Best-bet: Solutions or technologies considered most likely to give the best results over a range of different contexts.

Best-fit: Solutions or technologies most likely to give the best results in a particular context.

Blanket fertilizer recommendations: Fixed fertilizer recommendations that do not consider variability in soils, climate and crop sequences.

Buffering capacity: The extent to which a soil resists changes in pH. Soils containing large amounts of clay and organic matter have a high buffering capacity, which means that they will require large amounts of lime to increase soil pH. Soils with a low buffering capacity such as sandy soils with little organic matter require less lime to increase the soil pH (source: http://en.wikipedia.org/wiki/Buffer_solution).

Competing claims: When different stakeholders with divergent interests are seeking to use the same limited resource at the same time.

Conservation agriculture: Cropping and land management system that involves reduced tillage, crop residue retention, the use of crop rotation and crop diversification (source: http://www.fao.org/ag/ca/).

Conservation tillage: A form of tillage that leaves at least 30% of previous crop residues on the soil surface (source: http://www.mda.state.mn.us/protecting/conservation/practices/constillage.aspx).

Crop residues: The part of the crop biomass that is left when the economic yielding part such as the grain or tuber has been removed.

Crop rotation: A temporal sequence of different crops cultivated in the same field.

Degraded soil: A soil deficient in nutrients and depleted in organic matter, with little biological activity and poor soil structure.

Dis-adoption: When farmers that participated in a project revert back to their previous practices after the project promoting new practices has ended.

Dryland farming: When crops are grown in low-rainfall areas without irrigation.

Ecology: The study of the relationships that living organisms have with each other and their natural environment (source: http://en.wikipedia.org/wiki/Ecology).

Eutrophication: Excessive growth of algae or aquatic plants due to the presence of large concentrations of phosphates and nitrates. The subsequent decomposition of algae often leads to oxygen depletion, causing the death of other organisms (source: http://en.wikipedia.org/wiki/Eutrophication).

***Ex ante* analysis:** An assessment of the expected impact of an intervention prior to implementation (source: http://en.wikipedia.org/wiki/Ex-ante).

***Ex post* analysis:** An evaluation of the observed impact of an intervention after implementation. Proper impact evaluations determine the conditions where an intervention worked well and where it did not.

Fallow period: The period during which a field is rested in order to restore soil fertility.

Farm gate price: The price of produce the farmer would expect to receive when produce is sold directly from the farm.

Farm system: A household, its resources and the resource flows and interactions within a particular farm.

Farming system: A population of individual farm systems. The farming system includes the sub-systems of the farm, i.e. the crop and livestock systems, and the common land that is used for grazing, collecting of firewood and fruits, etc.

Farmyard manure: A mixture of dung and urine from farm animals, litter and leftover material from roughages or fodder fed to livestock after undergoing partial decomposition (source: http://agritech.tnau.ac.in/org_farm/orgfam_manure.html).

Georeference: The grid coordinates that define the spatial position of an object, or the process of defining those coordinates.

Grain legume: A legume crop grown primarily for its grain yield.

Green Revolution: A series of research, development and technology transfer initiatives occurring between the 1940s and the late 1970s, designed to increase agricultural production (source: http://en.wikipedia.org/wiki/Green_Revolution).

Growth-limiting: Factors such as water and nutrients or feed and foraging time that limit the growth of crops and livestock, respectively.

Growth-reducing: Factors such as pests, weeds, diseases and pollutants that reduce the growth of crops and livestock.

Hardpan: Dense sub-surface layer of soil that is impervious to water. Mainly formed by compaction from repeated ploughing with mouldboard ploughs and/or heavy vehicular traffic.

Heterogeneity: Lack of uniformity. Used to describe the variability in soil fertility status within and across farms due to differences in management.

Home fields: Fields located close to the homestead that are generally well managed and receive larger inputs of fertilizer and labour. See **Out fields**.

Hyphae: Long branches of fungus structures that are the main mode of vegetative growth of fungi.

Inoculation: The process of applying commercially produced rhizobial inoculants to legume seed or to the soil where legume seed will be planted to introduce compatible and effective symbiotic bacteria and improve nodulation and biological nitrogen fixation.

Intensification: Practices that results in increases in productivity per unit land area, involving changes in resource use (e.g. labour, external inputs).

Intercropping: The cultivation of two or more crops on the same piece of land. Crops can be planted at different times but growing periods should overlap.

Judicious: According to precise or sound judgement.

Leaching: Movement of crop nutrients beyond the root zone mainly due to excessive drainage in coarse textured soil.

Liming: Application of an alkaline material (e.g. agricultural lime) such as ground dolomitic limestone to increase the pH of the soil to the level required for plant growth.

Livelihood: The means of securing the necessities of life, the command an individual has over income and resources that can be used or exchanged to satisfy basic needs (source: http://en.wikipedia.org/wiki/Livelihood).

Low-input agriculture: Use of small amounts of inputs to lower production costs and reduce the possible negative effects that external inputs (e.g. fertilizers) might have on the environment.

Macronutrients: Nutrients required by plants in large quantities (i.e. nutrients that constitute at least 0.1% of plant dry matter).

Market orientation: Where crop or livestock products are primarily sold on the market rather than used for home consumption.

Micronutrients: Nutrients required by plants in small quantities (i.e. nutrients that constitute less than 0.1% of plant dry matter), often sufficient in most soils (source: http://en.wikipedia.org/wiki/Micronutrient).

Model: A simple representation of a system.

Multinutrient fertilizers: Fertilizers containing more than one nutrient (e.g. diammonium phosphate, compound fertilizer 15-15-15).

Mycorrhizal fungi: Fungi that form a symbiotic association with the roots of a vascular plant and improve nutrient uptake by the plant.

Nutrient deficiency: Demand for nutrients is greater than the soil supply, resulting in reduced or impaired plant growth.

Nutrient mining: Nutrient removal in crop products and biomass exceeds replenishment by the addition of crop residues, farmyard manure and fertilizers.

Nutrient omission trials: Trials to identify which nutrients limit plant growth. Treatments usually include +N+P+K+Mg, –N+P+K+Mg, +N–P+K+Mg, +N+P–K+Mg, +N+P+K–Mg, and –N–P–K–Mg.

Nutrient toxicity: Soil nutrient supply exceeds plant demand to such an extent that growth is impaired rather than enhanced.

Optimize: Make the most effective or best possible use of a resource.

Out fields: Fields that are more distant from the homestead, which receive less nutrient inputs and labour investment than home fields.

Parent material: The material from which soils are formed (usually rocks or saprolite).

Partial budget: In the context of soil fertility management in a farm system, a partial budget is used to assess the economic impacts of a proposed change in farm management practices by considering changes in the particular inputs and outputs that are affected by the changes in farm management practices.

Pernicious weeds: Weeds that are particularly competitive with or destructive of crop plants.

Primary driver: The most influential factor determining the outcome in a particular process.

Primer: Introduction to a subject that can be used for teaching.

Productivity gap: The difference between actual farmer productivity and attainable productivity using best management practices.

Promiscuous: In the context of biological nitrogen fixation, describes a legume that can form an effective symbiosis with many strains of rhizobia, or a rhizobial strain that can form nodules with many host plants.

Resource endowment: The resources for agricultural production that are at the farmer's disposal.

Resource flow maps: Visual representation of the movement of nutrients, labour, crop products, crop residues and animal manures within and between farms.

Responsive soils: Soils that show a large response to the application of crop nutrients.

Rhizobia: Bacteria present in the soil that form root nodules with compatible legume plants and are able to fix atmospheric nitrogen (N_2) within the nodules.

Rhizobial inoculants: Commercial products used to introduce rhizobia to ensure nodulation and nitrogen fixation in legume plants. Inoculants must be compatible with the host legume species and are applied to the legume seed before planting or in the furrow at planting. Inoculants are only required when compatible, effective rhizobia are not present in the soil in sufficient numbers.

Risk: The probability of crop failure due to the effects of drought, pests and diseases, and market failure.

Sensitivity analysis: The study of how uncertainty in the outcome of a process can be apportioned to different sources of uncertainty in inputs. Used to improve understanding or quantification of a farming system (i.e. the relationship between input and output variables).

Shifting cultivation: Fields are cultivated for a short period of 1–3 years and then fallowed in order to replenish soil fertility.

Socio-ecological niches: The agroecological and socio-economic conditions to which a particular intervention is suited.

Soil acidity: A measure of the hydrogen ion (H^+) concentration in the soil. Acid soils have a pH less than 7.

Soil capital: Soil, including its nutrient stocks, viewed as a capital asset.

Soil fertility gradients: Differences in soil fertility caused by differences in crop management (e.g. application of organic and mineral fertilizers) within a farm over the long term (source: http://library.wur.nl/isric/fulltext/isricu_i25173_001.pdf).

Soil health: The physical, chemical and biological fertility of soil.

Soil porosity: The amount of space filled with air and water between soil particles (source: http://www.noble.org/ag/soils/soilwaterrelationships/).

Soil texture: The amount of sand, silt and clay in the soil mineral fraction.

Spot application: When fertilizer is applied to each planting hill as opposed to being broadcast over the soil surface.

Subsidy: A cash payment, tax reduction or incentive awarded by government to protect the interests of farmers, to remove a financial burden, or to encourage the purchase of agricultural inputs or the sale of an agricultural product.

Sustainable development: Development where resource use meets human needs without compromising the ability to meet human needs in the future.

Symbiosis: An interaction between two different organisms living in close physical association that is to the advantage of both organisms.

Trade-off: A situation that involves losing one quality or aspect of something in return for gaining another (source: http://en.wikipedia.org/wiki/trade-off).

Yield gap: The difference between actual farmer yield and attainable yield. Attainable yield is the maximum yield observed in a given agroecological zone when best management practices are used.

Acronyms and abbreviations

AE	Agronomic efficiency
AGRA	Alliance for a Green Revolution in Africa
Al	Aluminium
AMF	Arbuscular mycorrhizal fungi
ASHC	Africa Soil Health Consortium
B	Boron
C	Carbon
Ca	Calcium
CA	Conservation agriculture
$Ca(OH)_2$	Calcium hydroxide
CABI	CAB International
$CaCO_3$	Calcium carbonate
$CaMg(CO_3)_2$	Dolomite
CaO	Calcium oxide
$CaSO_4.2H_2O^-$	Gypsum
CCE	Calcium carbonate equivalent
CEC	Cation exchange capacity
CIAT	International Centre for Tropical Agriculture
CKW	Community knowledge worker
Cl	Chlorine
Co	Cobalt
Cu	Copper
DAP	Diammonium phosphate
DRC	Democratic Republic of Congo
F/O	Fertilizer/output
Fe	Iron
FSA	Farming systems analysis
GMO	Genetically modified organism
GPS	Global positioning system
H^+	Hydrogen ion
HI	Harvest index
ICRAF	World Agroforestry Centre
ICRW	International Centre for Research on Women
ICT	Information and communication technologies
IFDC	International Fertilizer Development Centre
IITA	International Institute of Tropical Agriculture
IPNI	International Plant Nutrition Institute
IRRI	International Rice Research Institute
ISFM	Integrated Soil Fertility Management
K	Potassium
K_2SO_4	Potassium sulfate
KCl	Potassium chloride
LEISA	Low external input sustainable agriculture
LER	Land equivalent ratio
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum

MSU	Michigan State University
N	Nitrogen
Na	Sodium
NH_3	Ammonia
NH_4^+	Ammonium
Ni	Nickel
NO_3	Nitrate
NPK	Nitrogen phosphorus potassium
O	Oxygen
PR	Phosphate rock
RF	Recovery fraction
S	Sulfur
Si	Silicon
SMS	Short message service (text)
SOFECSA	Soil Fertility Consortium for Southern Africa
SOM	Soil organic matter
SSA	Sub-Saharan Africa
SSP	Single superphosphate
TAG	Technical advisory group
TCC	Tropical Crop Consultants Ltd
TSP	Triple superphosphate
USAID	US Agency for International Development
VCR	Value:cost ratio
WUR	Wageningen University
Zn	Zinc

Index



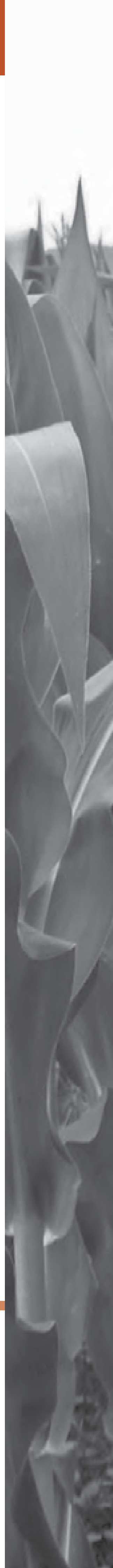

This handbook presents Integrated Soil Fertility Management, commonly known as ISFM, as a key contributor to improving Africa's soil and crop productivity, especially for the key staples in the continent that include maize, legumes, rice, cassava, bananas, sorghum, millet and coffee.

It is meant for training of extension workers on soil fertility management techniques in sub-Saharan Africa and for workers involved in rural development that would like to learn more about the principles of ISFM.

The handbook is also a useful primer on ISFM for educational organizations such as universities and technical colleges, and organizations involved in the development of policy on agriculture and rural development that need reference materials on ISFM techniques.

Produced by the Africa Soil Health Consortium (ASHC), this handbook is part of a series of materials and publications on ISFM produced for stakeholders including extension personnel, smallholder farmers, agro dealers, policy makers and training institutions. Other materials include cropping and plant nutrition guides, policy briefs, training manuals and practical information for extension workers and farmers. See the ASHC website for further details: **www.cabi.org/ashc**

The ASHC works with initiatives in sub-Saharan Africa to encourage the uptake of ISFM practices. ASHC is coordinated by CABI in partnership with international and national science and agriculture organizations with support from the Bill & Melinda Gates Foundation.



The Africa Soil Health Consortium is coordinated by CABI. CABI is also the publisher of this hand book.

The Communications Unit, Africa Soil Health Consortium, CABI, ICRAF Complex,
P.O. Box 633-00621 Nairobi, Kenya
Tel: +254-20-722 4450/62 Fax: +254-20-712 2150 Email: Africa@cabi.org
Website: www.cabi.org/ashc

978 1 78064 291 8

Published: August 2014